Low Energy Tests of the Standard Model and its Fundamental Symmetries

Gerald Gabrielse
Leverett Professor of Physics, Harvard University

60 years of since parity violation

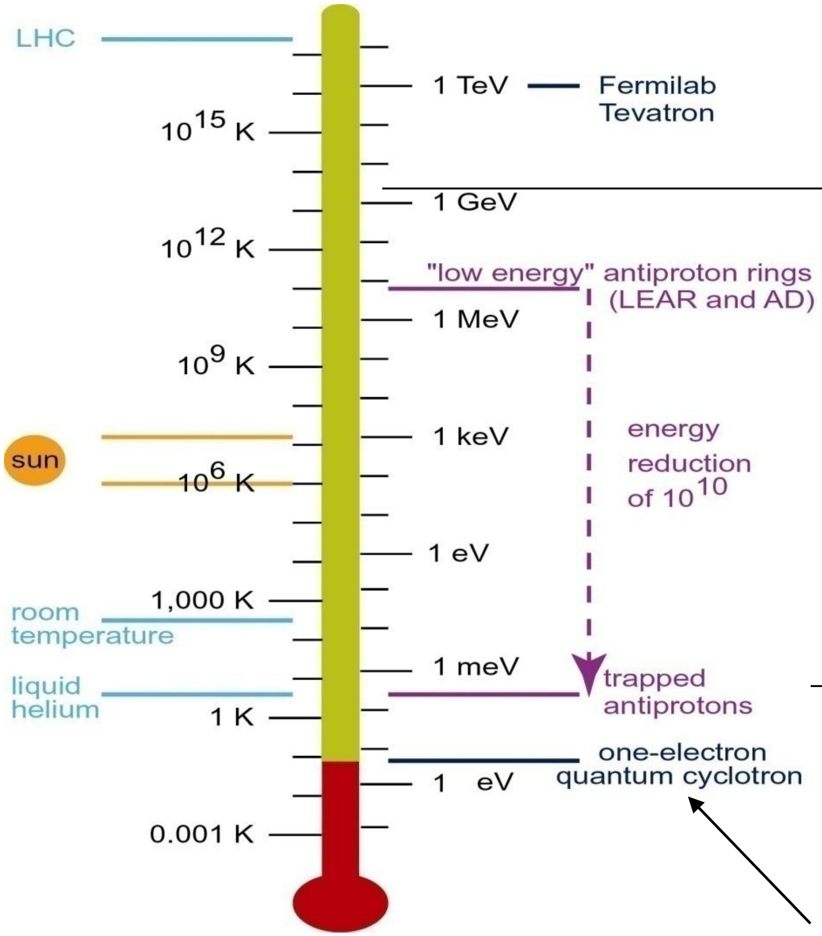
Inspired by the experiment of Wu, and the proposal of Lee and Yang,
→ small-scale, low-energy experiments
to investigate the particles, interactions, and symmetries of the universe,
to test and help develop our most fundamental theoretical descriptions.

N$F and AFO$R

Low Energy Particle Physics

AMO Physics, Particle Physics, Plasma Physics

methods and funding ↗ goals and facility ↑ ↖ can't avoid



$2M_pc^2$

LEAR and AD

10^{10}

TRAP 4.2 K

0.3 meV

70 mK, lowest storage energy for any charged particles

New in 2017

Center for Fundamental Physics at Low Energy

(cfp.physics.northwestern.edu)

Specializing in small-scale, low-energy experiments
- to investigate the particles, interactions, and symmetries of the universe
- to test and help develop our most fundamental theoretical descriptions.

Exciting opportunities available for

- New faculty members -- need promise to do Wu-like experiments
- CFP postdocs – need aspire to do Wu-like experiments
- Graduate students – need to desire a Wu-like adventure

Founding director: G.G.
First faculty search starts: Fall 2016 (contact G.G.)

Stringent Low Energy Tests of the Standard Model and Its Symmetries

Illustrate with experiments that have 3 kinds of objectives

1. Testing the Standard Model's most precise prediction
   by making the most precise measurement
   of a property of an elementary particle

electron magnetic dipole moment

2. Testing very different predictions of the Standard Model
   and Supersymmetry (and other) models

electron electric dipole moment

also neutron, proton, Hg

3. Testing the most fundamental symmetry of the Standard Model

q/m for antiproton and proton

mag. moments of e^+ and e^-

The Standard Model → The Great Triumph and the Great Frustration of Modern Physics

Start with frustration

Embarrassing, Unsolved Mystery: How did our Matter Universe Survive Cooling After the Big Bang?

Big bang → equal amounts of matter and antimatter created during hot time

As universe cools → antimatter and matter annihilate

Big Questions:

- **How did any matter survive?**
- **How is it that we exist?**

Our experiments are looking for evidence of any way that antiparticles and particles may differ

Our "Explanations" are Not so Satisfactory

Baryon-Antibaryon Asymmetry in Universe is Not Understood

Standard "Explanation"

- CP violation
- Violation of baryon number
- Thermodynamic non-equilibrium

Sakarov

Alternate

- CPT violation
- Violation of baryon number
- Thermo. equilib.

Bertolami, Colladay, Kostelecky, Potting
Phys. Lett. B 395, 178 (1997)

Why did a universe made of matter survive the big bang?
Makes sense look for answers to such fundamental questions in the few places that we can hope to do so very precisely.

Bigger problem: don't understand dark energy within 120 orders of magnitude

Why Compare H and $\bar{H}$ (or P and $\bar{P}$)?

Reality is Invariant – symmetry transformations

~~P~~ parity
~~CP~~ charge conjugation, parity
CPT charge conjugation, parity, and time reversal

CPT Symmetry

→ Particles and antiparticles have

- same mass
- opposite charge
- same magnetic moment
- same mean life

→ Atom and anti-atom have

→ same structure

Looking for Surprises

- simple systems
- extremely high accuracy
- comparisons will be convincing
- reasonable effort
- FUN

High Precision Tests of CPT Invariance

The Most Precise CPT Test with Baryons → by TRAP at CERN

G. Gabrielse, A. Khabbaz, D. S. Hall, C. Heimann, H. Kalinowsky, and W. Jhe, Phys. Rev. Lett. **82**, 3198 (1999).

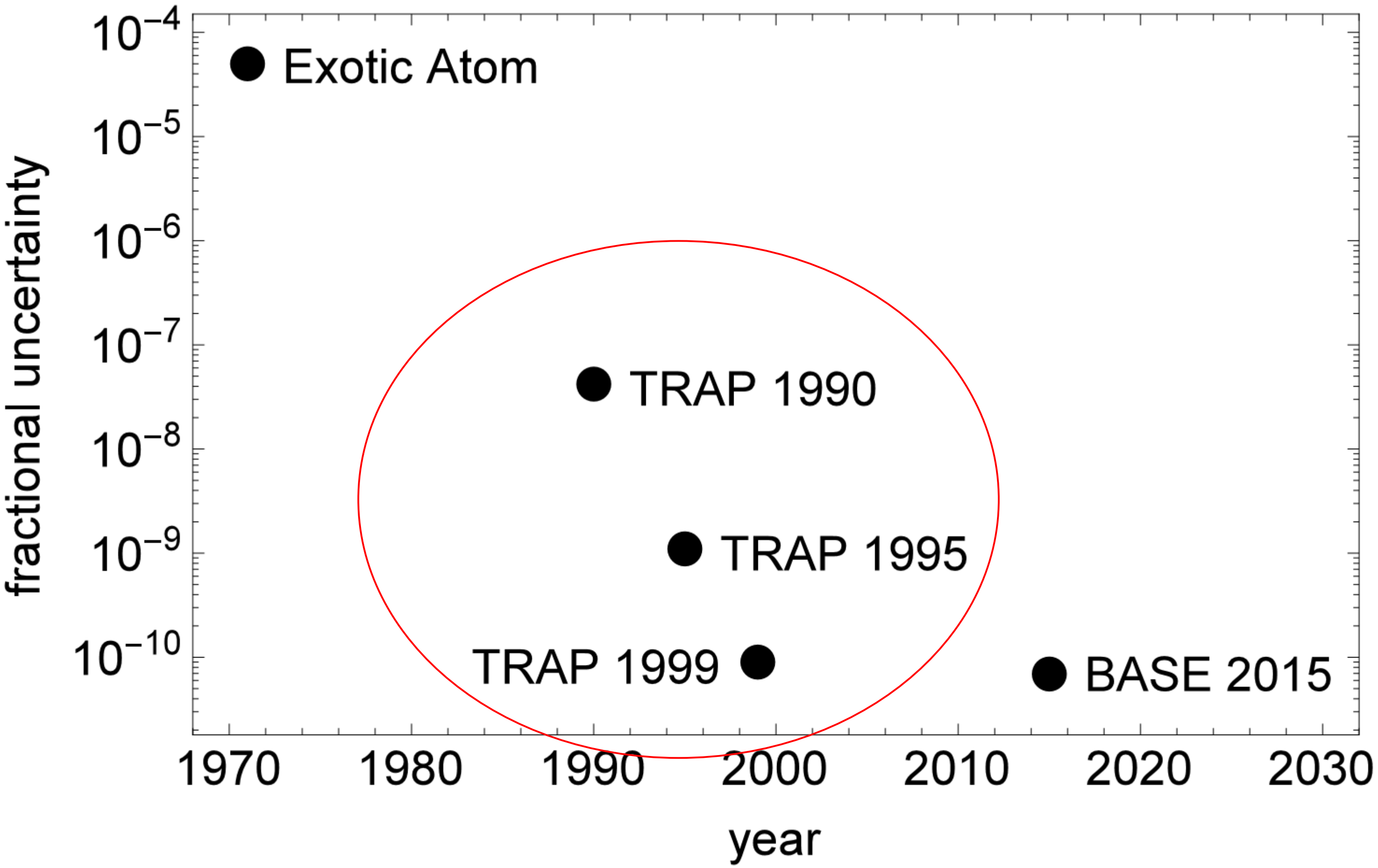
$$\frac{q/m\ \text{(antiproton)}}{q/m\ \text{(proton)}} = -0.99999999991(9)$$

$$9\times10^{-11} = 90\,\text{ppt}$$

(most precise result of CERN’s antiproton program before the AD)

Goal at the AD: Make CPT tests that approach
or exceed this precision

Uncertainty in Comparison of Q/M for the Antiproton and Proton



Comparing the CPT Tests

Warning – without CPT violation models it is hard to compare

3 fundamentally different types of particles

	CPT Test Accuracy	Measurement Accuracy	Free Gift
$K_0 \overline{K}_0$ Mesons	2×10^{-18}	2×10^{-3}	10^{15}
$e^+ e^-$ Leptons	2×10^{-12}	2×10^{-9}	10^{3}
$P \overline{P}$ baryons	9×10^{-11}	9×10^{-11}	1

improve with antihydrogen

Direct Comparison of Antimatter and Matter Gravity

Does antimatter and matter accelerate at the same rate in a gravitational field?

$$g_{antimatter} = \kappa \, g_{matter}$$

acceleration due to gravity
for antimatter

acceleration due to gravity
for matter

The Most Precise Experimental Answer is “Yes” → to at lease a precision of 1 part per million

Gravitational red shift for a clock: $\Delta\omega/\omega = g\,h/c^2$

→ Antimatter and matter clocks run at different rates
if g is different for antimatter and matter

$$\frac{\Delta\omega_c}{\omega_c} = 3(\kappa - 1)\frac{U}{c^2}$$

Hughes and Holzscheiter,
Phys. Rev. Lett. 66, 854 (1991).

grav. pot. rnergy difference
between empty flat space time
and inside of hypercluster of galaxies

for tensor gravity
(would be 1 for scalar gravity)

Experiment: TRAP Collaboration, Phys. Rev. Lett. 82, 3198 (1999).

$$\frac{\Delta\omega_c}{\omega_{\partial c}} < 10^{-10} \qquad --> \qquad \kappa = 1 \pm \;(<10^{-6})$$

Comparable limit to that on neutrinos and antineutrinos 1987A

Comparison of an Antimatter and Matter Clock

The Most Precise CPT Test with Baryons → by TRAP at CERN

G. Gabrielse, A. Khabbaz, D. S. Hall, C. Heimann, H. Kalinowsky, and W. Jhe, Phys. Rev. Lett. **82**, 3198 (1999).

$$\frac{q/m\ \ (\text{antiproton})}{q/m\ \ (\text{proton})} = -0.99999999991(9)$$

$$9\times 10^{-11} = 90\,\text{ppt}$$

(most precise result of CERN's antiproton program)

Goal at the AD: Make CPT test that approaches and exceed this precision

Hard to Get the Part per Million Precision of the Redshift Limit with Antihydrogen and Hydrogen

$$g_{antimatter} = \kappa\, g_{matter}$$

Our TRAP gravitational redshift: $\frac{\Delta\omega_c}{\omega_{\partial c}} < 10^{-10}$

$$--> \quad 0.999\,999 < \kappa < 1.000\,001$$

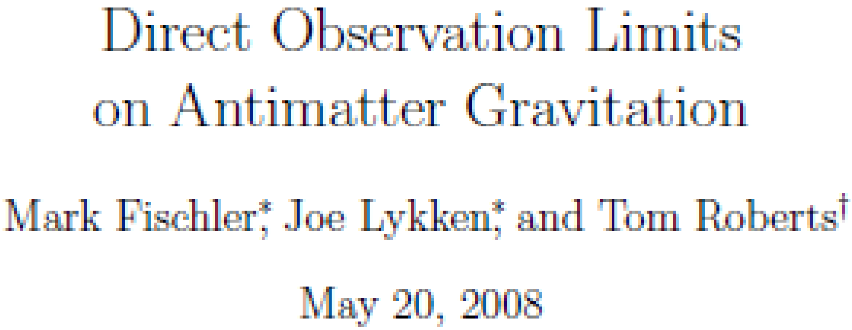
10^8

ALPHA trapped antihydrogen released (2013): $-110 < \kappa < 110$

(no mention direct redshift comparison)

Gravitational Redshift Comparison is Ignored citing an unpublished rational for a Fermilab gravity measurement proposal (not approved)

arXiv 0808.3929



Direct Observation Limits
on Antimatter Gravitation

Mark Fischler[*], Joe Lykken[*], and Tom Roberts[†]

May 20, 2008

- Perhaps CPT violations in the electromagnetic clocks cancel the CPT violation for gravity ← not likely
- If gravity would have a finite range then using the local supercluster of galaxies would not be appropriate ← adds violations
- Use of gravitational potential energy isn't sound ← not needed
  - → can use metric perturbation to flat space that must vanish at infinity to ensure that matter and antimatter look the same away from gravitational sources

How Much Better Could the Gravitational Comparison Be?

If we improve the charge-to-mass ratio measurement by a factor of 100
→ gravitation comparison will be 100 times more stringent

BASE is working on this.

We still hope to contribute but do not have enough time and people yet.

Electron Magnetic Dipole Moment

$$\vec{\mu} = \mu \, \frac{\vec{S}}{\hbar / 2}$$

Standard Model's Most Precise Prediction

$$\frac{e\hbar}{2m} \longrightarrow -\frac{\mu}{\mu_B} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots$$

$$+ \, \mathrm{a}_{hadronic} + a_{weak} + a_{new\ physics}$$

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \approx \frac{1}{137}$$

Dirac 1

QED

$$C_2 = 0.500\,000\,000\,000\,00 \; (\text{exact})$$

$$C_4 = -\,0.328\,478\,444\,002\,55\,(33)$$

$$C_6 = 1.181\,234\,016\,815\,(11)$$

$$C_8 = -\,1.909\,7\,(20)$$

$$C_{10} = 9.16\,(0.57).$$

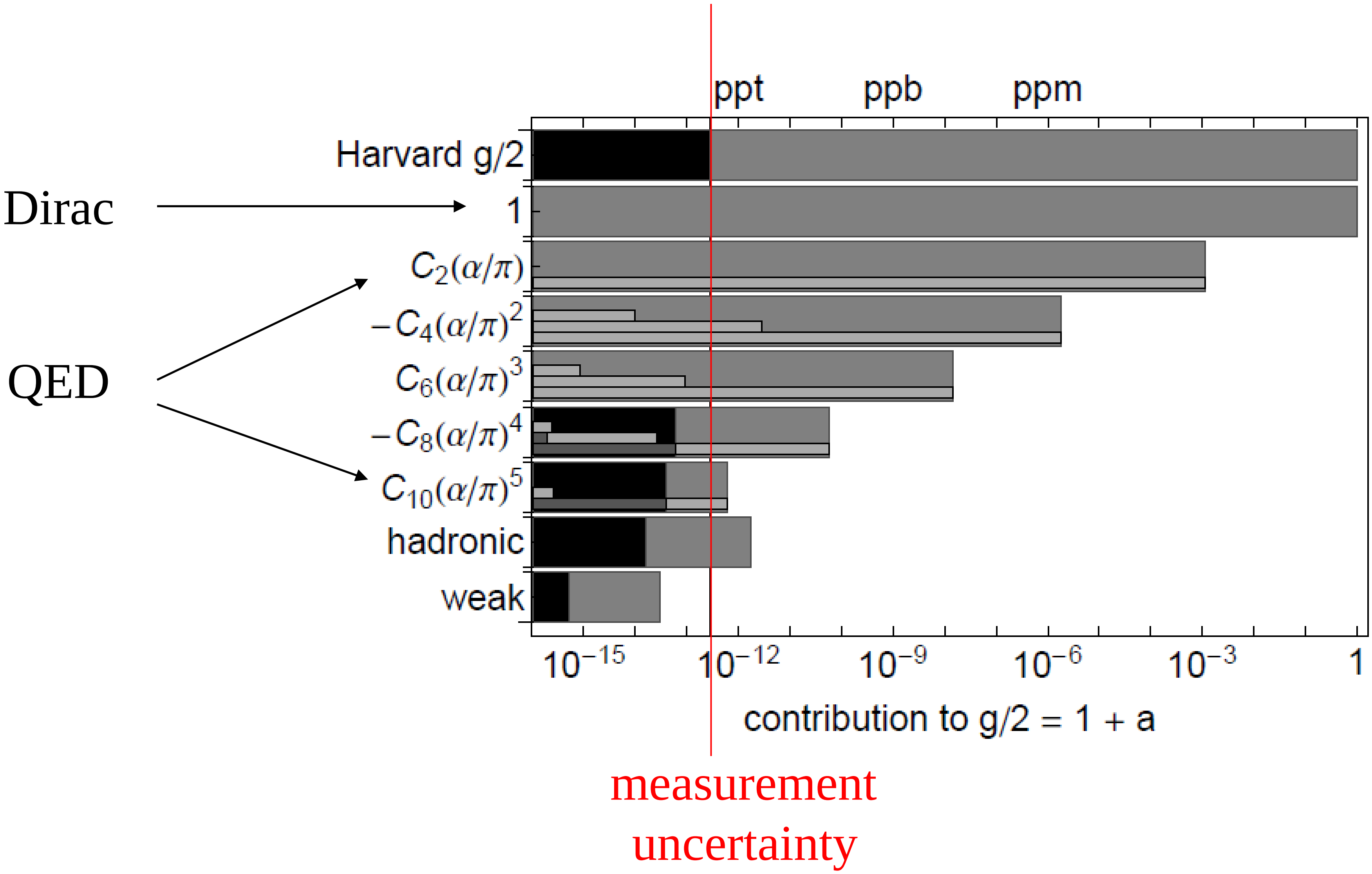
essentially exact

Kinoshita, Nio, …

Hadronic $a_e^{\text{hadronic}} = 1.677(16) \times 10^{-12}$

Weak a_{weak} smaller

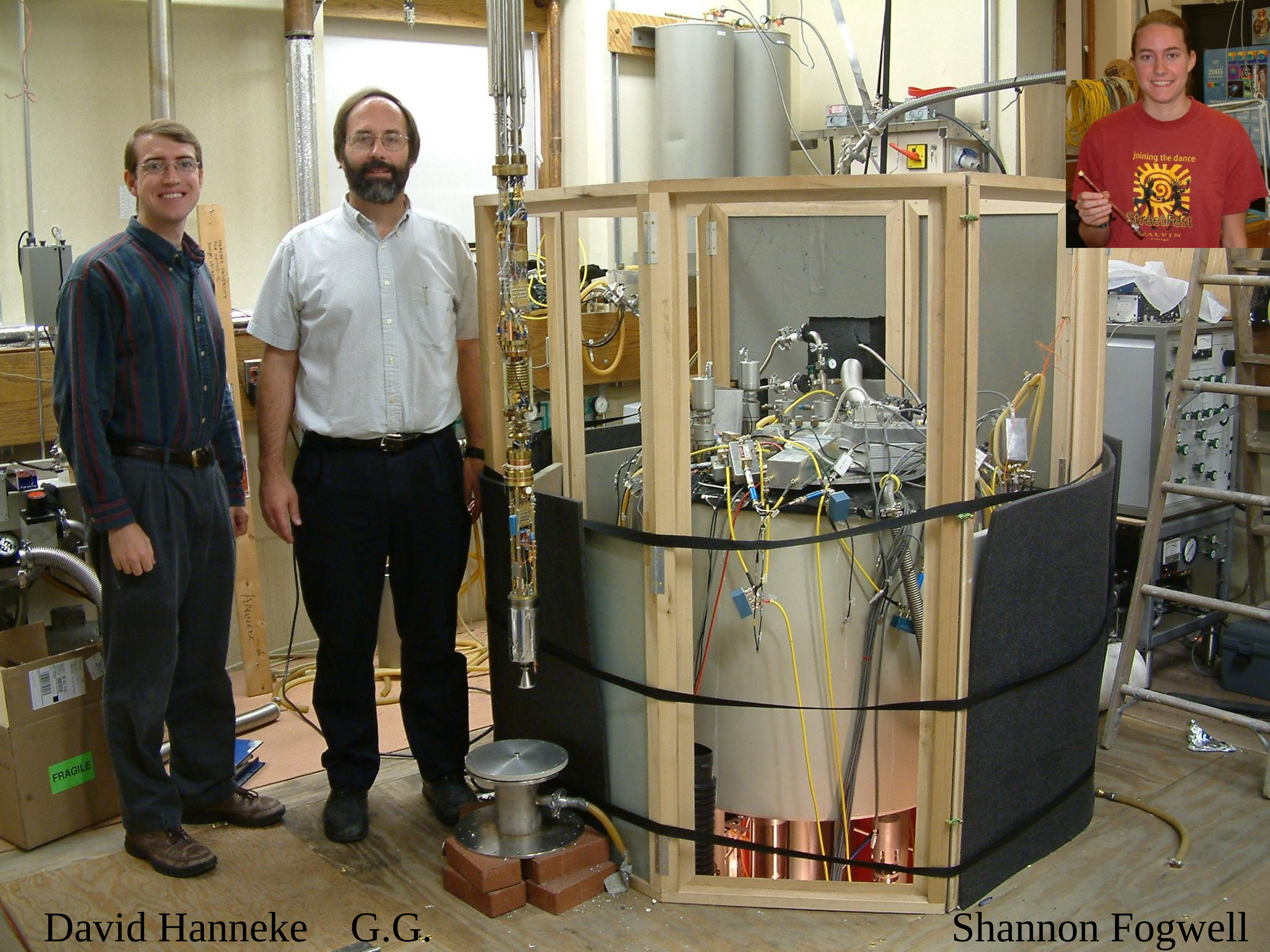
Probing 10th Order and Hadronic Terms



Dirac

QED

measurement uncertainty



David Hanneke G.G.

Shannon Fogwell

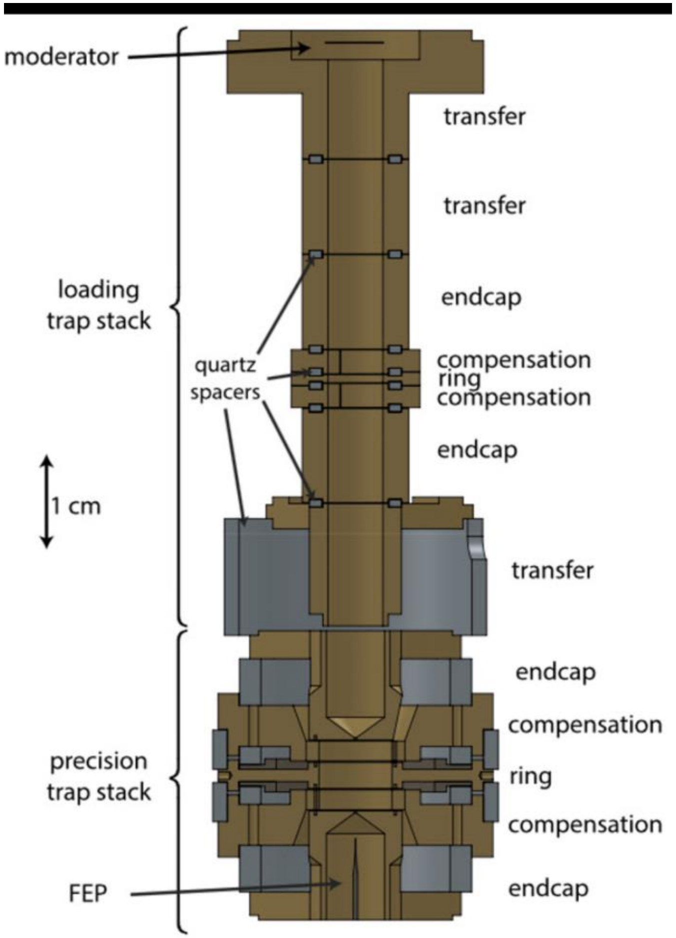
Need Good Students and Stable Funding

20 years
8 theses

Elise Novitski
Joshua Dorr
Shannon Fogwell Hogerheide
David Hanneke
Brian Odom,
Brian D’Urso,
Steve Peil,
Dafna Enzer,
Kamal Abdullah
Ching-hua Tseng
Joseph Tan

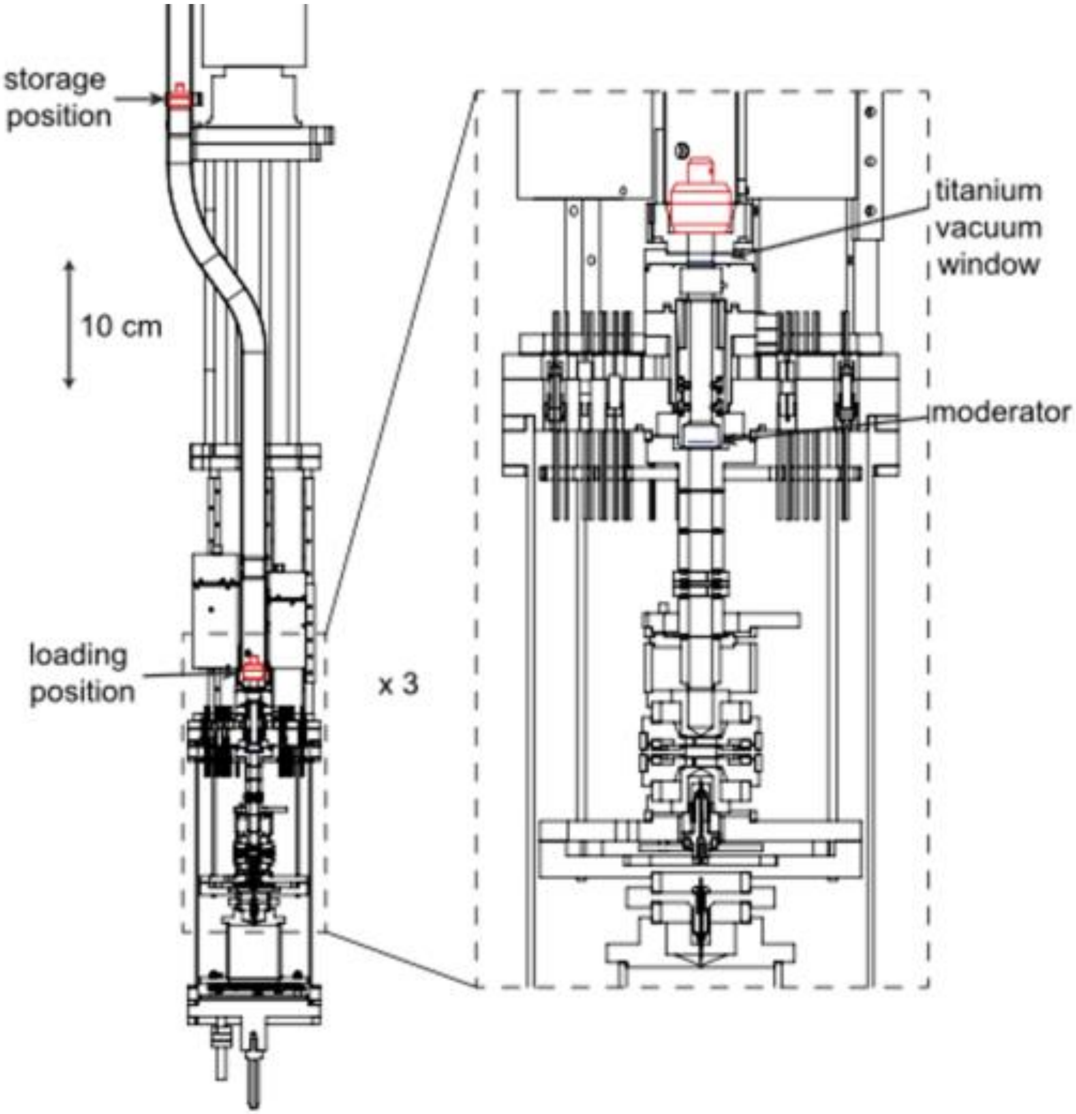
N$F

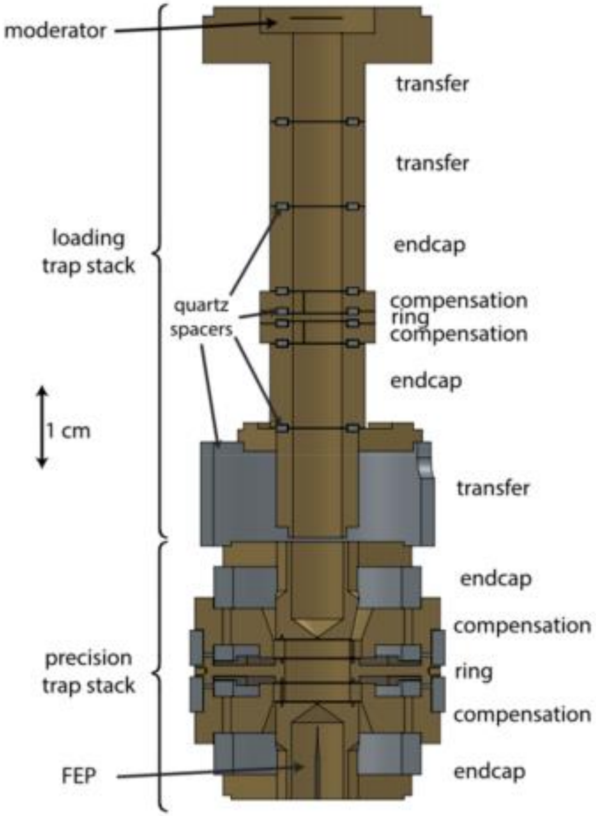
Current Team and Trap → e^- and e^+



Positron – electron trap
→ to compare magnetic moments
of the positron and electron

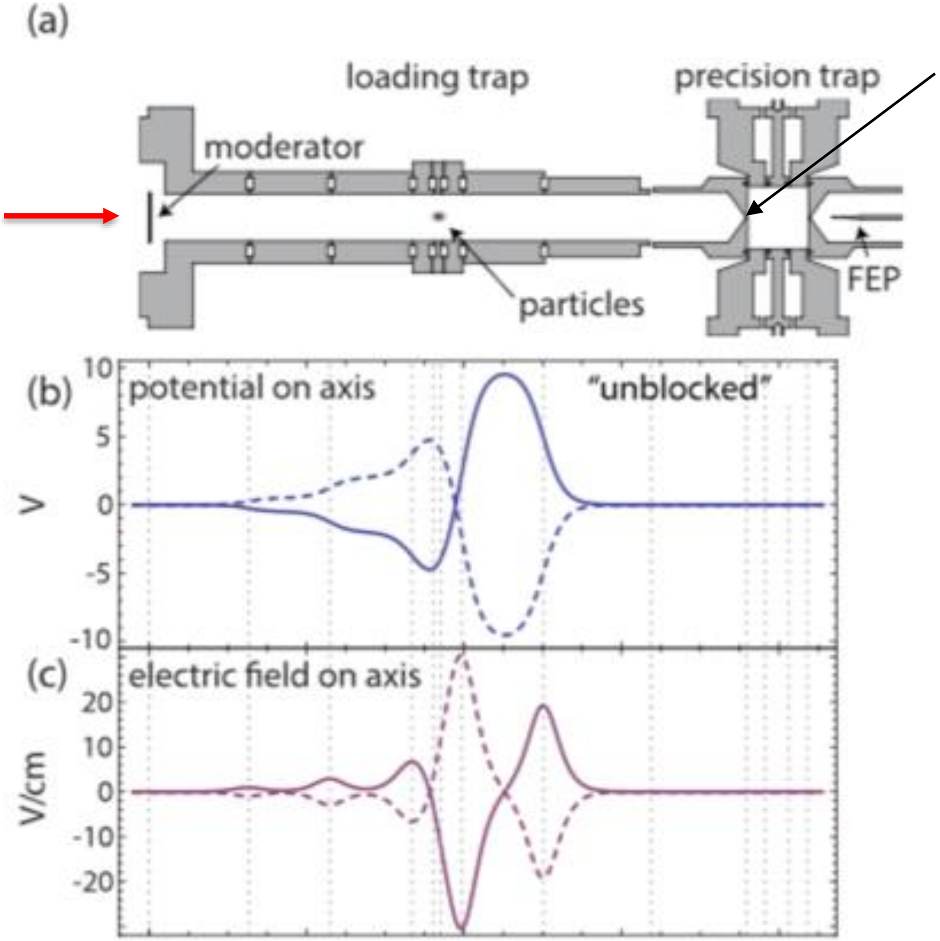
Capturing Positrons from a “Student Source”





Efficient Trapping of Positrons

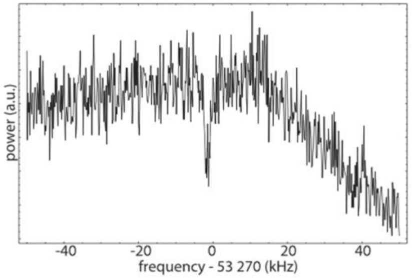
positrons
from Na^{22} →
source



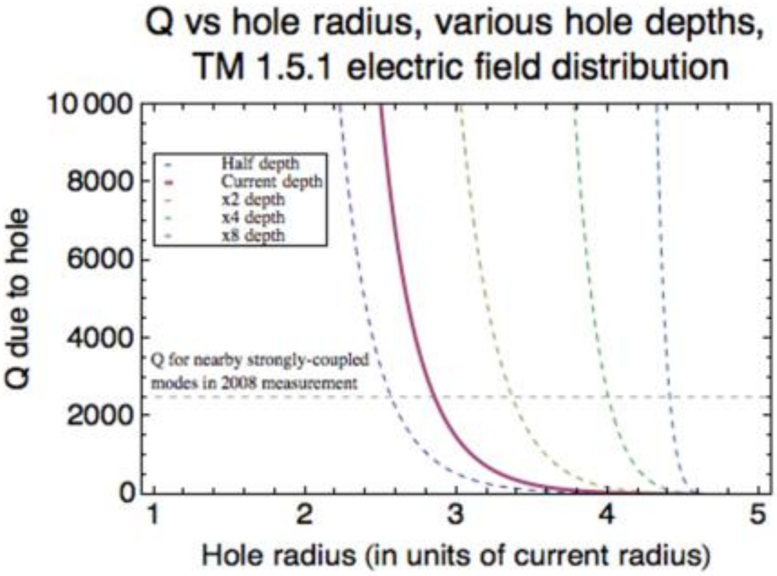
Small hole is giving us trouble

- Need small to keep low cavity loss (high Q)
- Need large enough to let positrons through

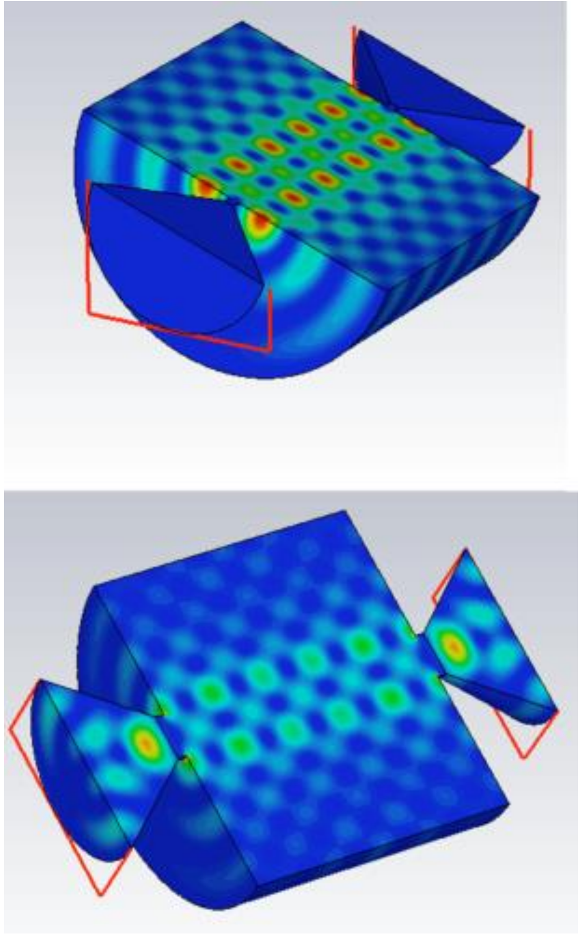
electrical signal
from ~ 200 positrons



More on the Hole

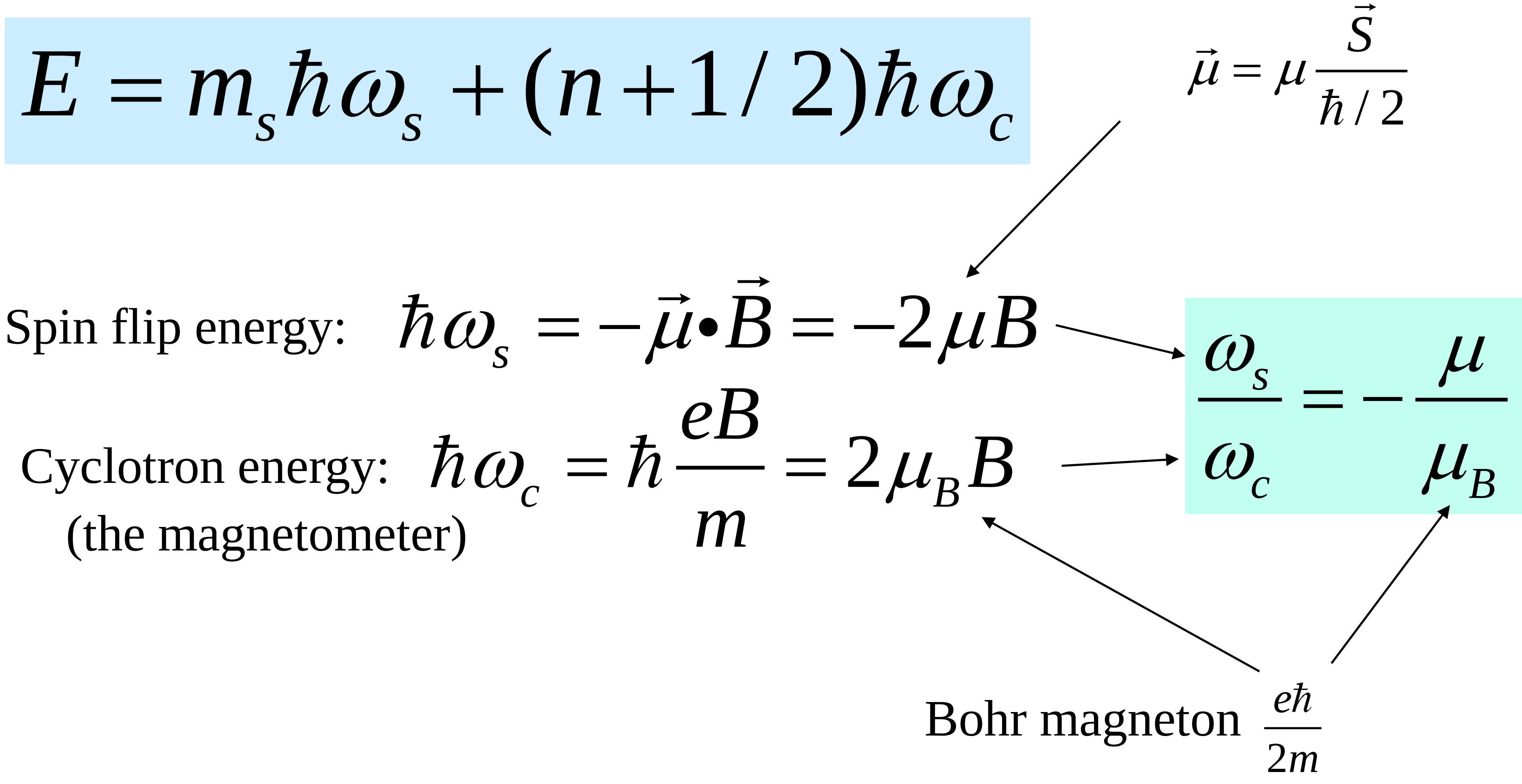


Q vs hole radius, various hole depths, TM 1.5.1 electric field distribution



Quantum Measurement of the Electron Magnetic Moment

$$E = m_s \hbar \omega_s + (n + 1/2)\hbar \omega_c$$



$$\vec{\mu} = \mu \frac{\vec{S}}{\hbar/2}$$

Spin flip energy: $\hbar \omega_s = -\vec{\mu} \bullet \vec{B} = -2\mu B$

Cyclotron energy: $\hbar \omega_c = \hbar \frac{eB}{m} = 2\mu_B B$

(the magnetometer)

$$\frac{\omega_s}{\omega_c} = -\frac{\mu}{\mu_B}$$

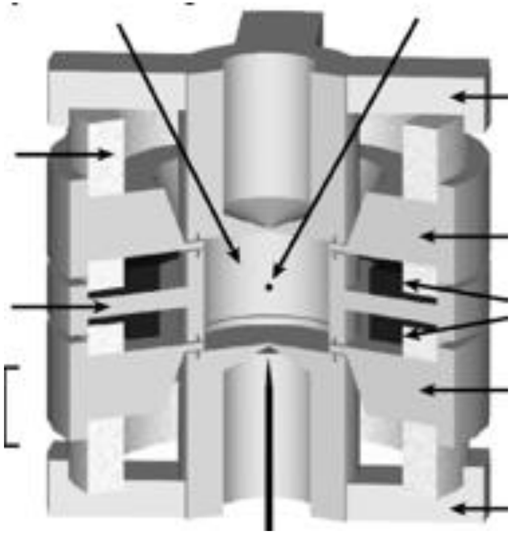
Bohr magneton $\frac{e\hbar}{2m}$

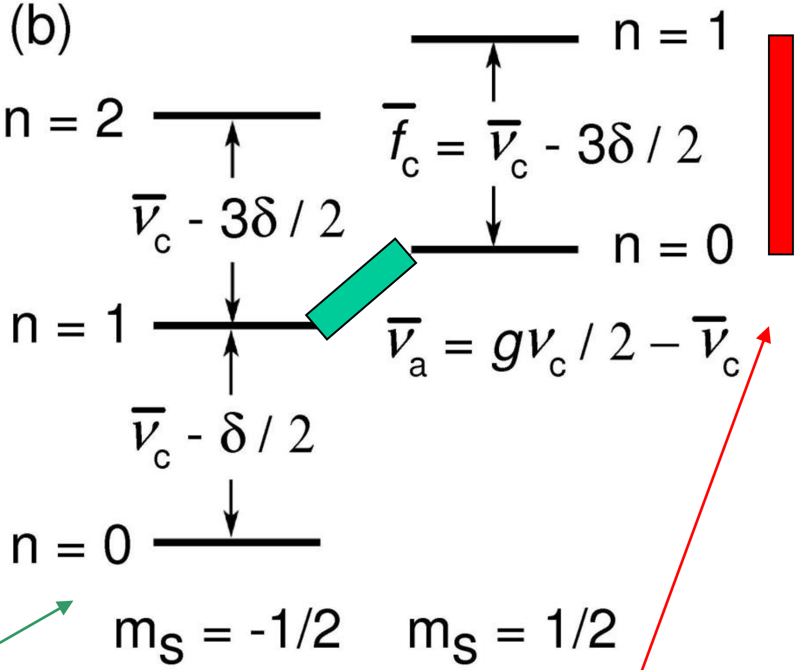
Need to resolve the quantum states of the cyclotron motion

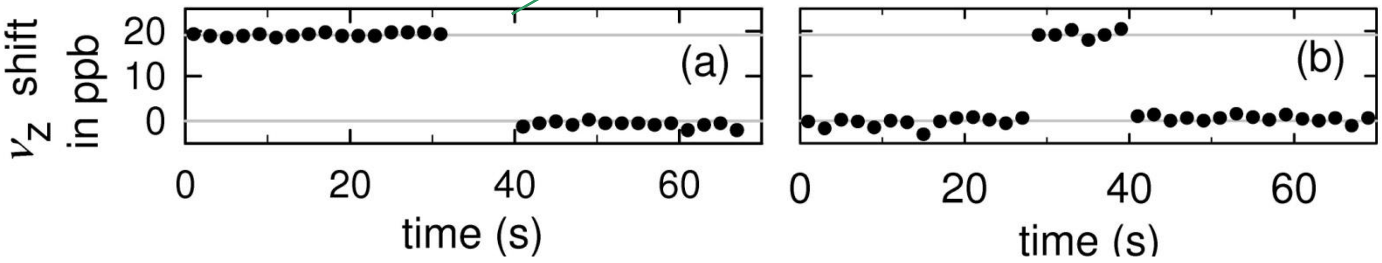
→ Relativistic shift is 1 part in 10^9 per quantum level

Most Precisely Measured Property of an Elementary Particle (2.8×10^{-13})

- one electron in a Penning trap
- lowest cyclotron and spin states







"New Measurement of the Electron Magnetic Moment and the Fine Structure Constant"
D. Hanneke, S. Fogwell and G. Gabrielse,
Phys. Rev. Lett. **100**, 120801 (2008) and arXiv:0801.1134v1 [physics.atom-ph].

SM Prediction Needs an Independent α

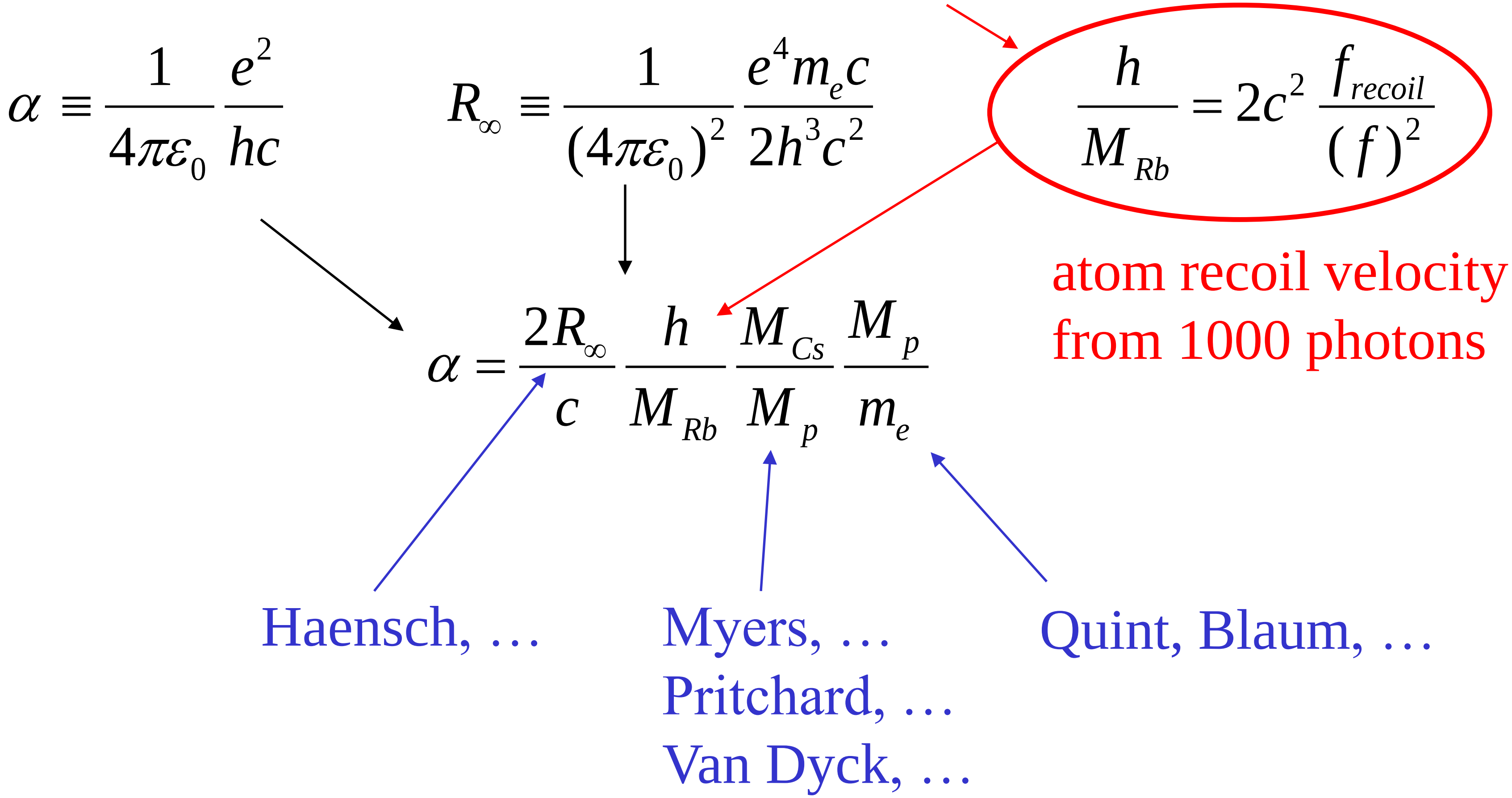
PRL 106, 080801 (2011) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

New Determination of the Fine Structure Constant and Test of the Quantum Electrodynamics

Rym Bouchendira,[1] Pierre Cladé,[1] Saïda Guellati-Khélifa,[2] François Nez,[1] and François Biraben[1]

[1]Laboratoire Kastler Brossel, Ecole Normale Supérieure, Université Pierre et Marie Curie, CNRS, 4 place Jussieu, 75252 Paris Cedex 05, France

[2]Conservatoire National des Arts et Métiers, 292 rue Saint Martin, 75141 Paris Cedex 03, France



$$\alpha \equiv \frac{1}{4\pi\varepsilon_0}\frac{e^2}{hc}$$

$$R_\infty \equiv \frac{1}{(4\pi\varepsilon_0)^2}\frac{e^4 m_e c}{2h^3c^2}$$

$$\frac{h}{M_{Rb}} = 2c^2\frac{f_{recoil}}{(f)^2}$$

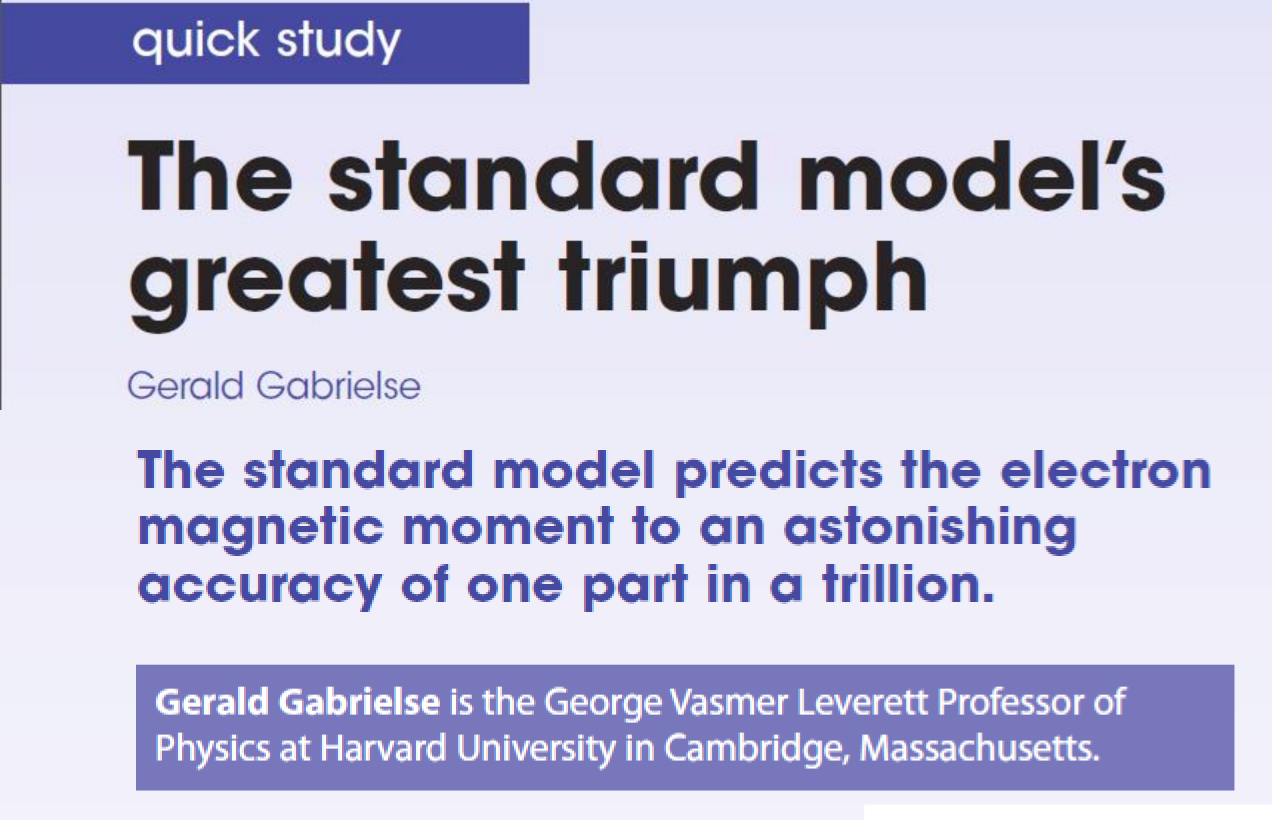
atom recoil velocity from 1000 photons

$$\alpha = \frac{2R_\infty}{c}\frac{h}{M_{Rb}}\frac{M_{Cs}}{M_p}\frac{M_p}{m_e}$$

Haensch, …

Myers, …
Pritchard, …
Van Dyck, …

Quint, Blaum, …



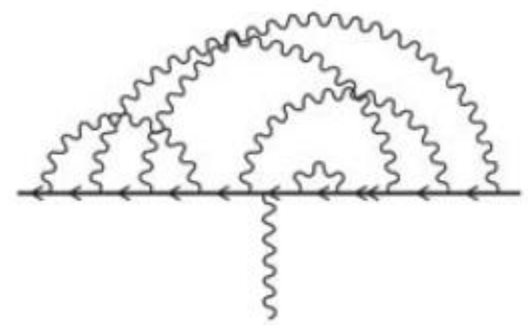
quick study

The standard model's greatest triumph

Gerald Gabrielse

The standard model predicts the electron magnetic moment to an astonishing accuracy of one part in a trillion.

Gerald Gabrielse is the George Vasmer Leverett Professor of Physics at Harvard University in Cambridge, Massachusetts.

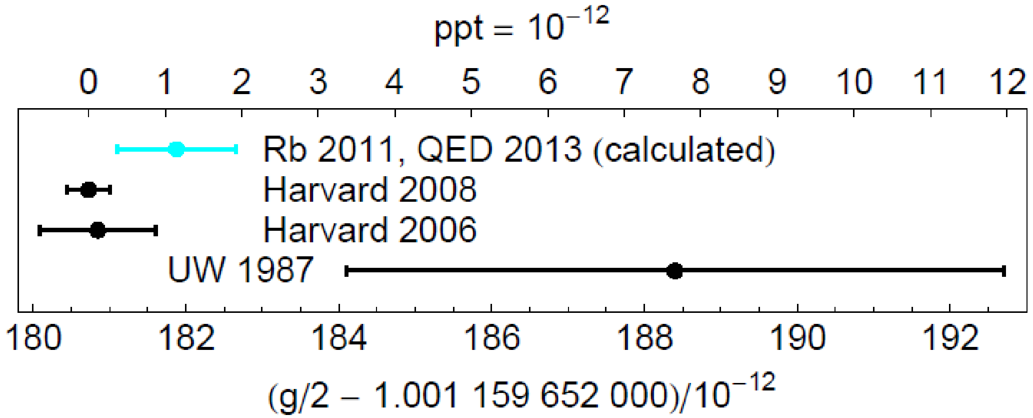


from measured
fine structure constant

Predicted: $\mu/\mu_B = -1.001\,159\,652\,181\,78\,(77)$

Measured: $\mu/\mu_B = -1.001\,159\,652\,180\,73\,(28)$

2.8×10^{-13}



64 December 2013 Physics Today www.physicstoday.org

Test for Physics Beyond the Standard Model

$$-\frac{\mu}{\mu_B} = \frac{g}{2} = 1 + a_{QED}(\alpha) + \delta a_{SM:Hadronic+Weak} + \delta a_{New\,Physics}$$

Does the electron have internal structure?

S. J. Brodsky and S. D. Drell. Anomalous Magnetic Moment and Limits on Fermion Substructure. *Phys. Rev. D*, 22:2236 – 2243, 1980.

$$m^* = \text{total mass of particles bound together to form electron}$$

$R < 5\times10^{-19}\ m$ $\qquad m^* > \frac{m}{\sqrt{\delta a}} = 360\ GeV/c^2$

limited by the uncertainty in independent α value

$R < 2\times10^{-19}\ m$ $\qquad m^* > \frac{m}{\sqrt{\delta a}} = 1\ TeV/c^2$

if our uncertainty was the only limit

Not bad for an experiment done at 100 mK, but LEP does better

$R < 2\times10^{-20}\ m$ $\qquad m^* > 10.3\ TeV/c^2$ $\qquad$ LEP contact interaction limit

> 20,000,000 electron masses of binding energy

Electron-Positron Summary

Already the most precise test of the standard model

Soon should be the most precise test of the standard model's most fundamental CPT symmetry (compare electron and positron)

Not so easy to improve on a magnetic moment already determined to 3 parts in 10^{13}, but progress continues toward a big improvement

One-electron Q-bit work has just restarted

Despite the Great Success of the Standard Model The Standard Model Cannot be the Whole Story

- Cannot explain how a matter universe exists (baryon imbalance is an unsolved mystery)
- Gravity does not fit well (can’t be renormalized)
- Cannot explain inflation
- Cannot explain dark energy

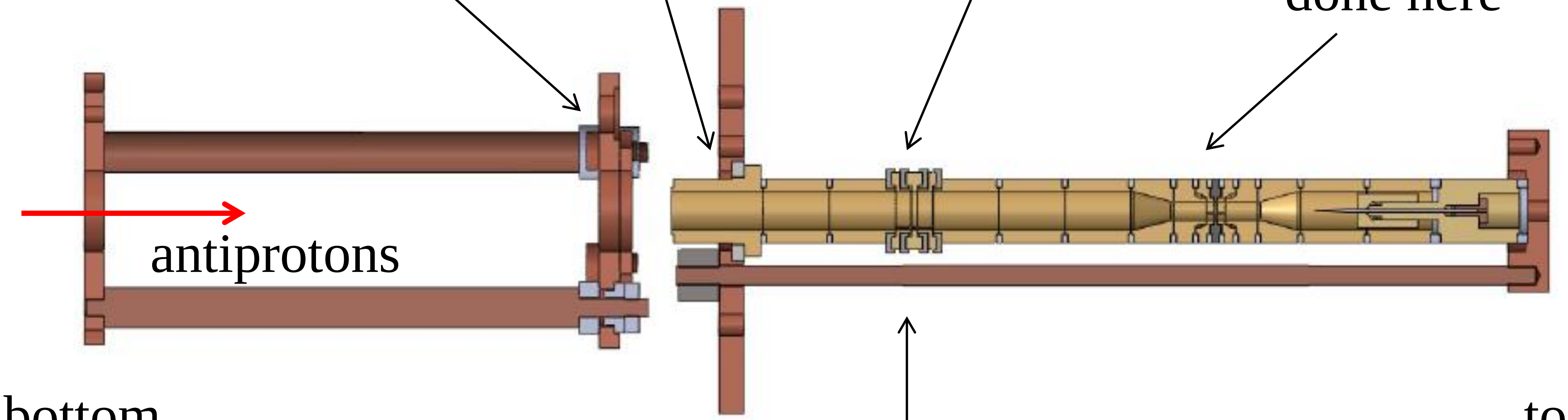
The standard model is the great success and great frustration of fundamental particle physics

Proton and Antiproton Magnetic Moments are Much Smaller

Harder: nuclear magneton rather than Bohr magneton

$$\mu_N/\mu_B = m_e/m_p \sim 1/2000$$

For Magnetic Moments: Three Antiproton Traps



degrader

catch and cool
antiprotons

cyclotron
cooling
trap

proton and antiproton
measurements
done here

antiprotons

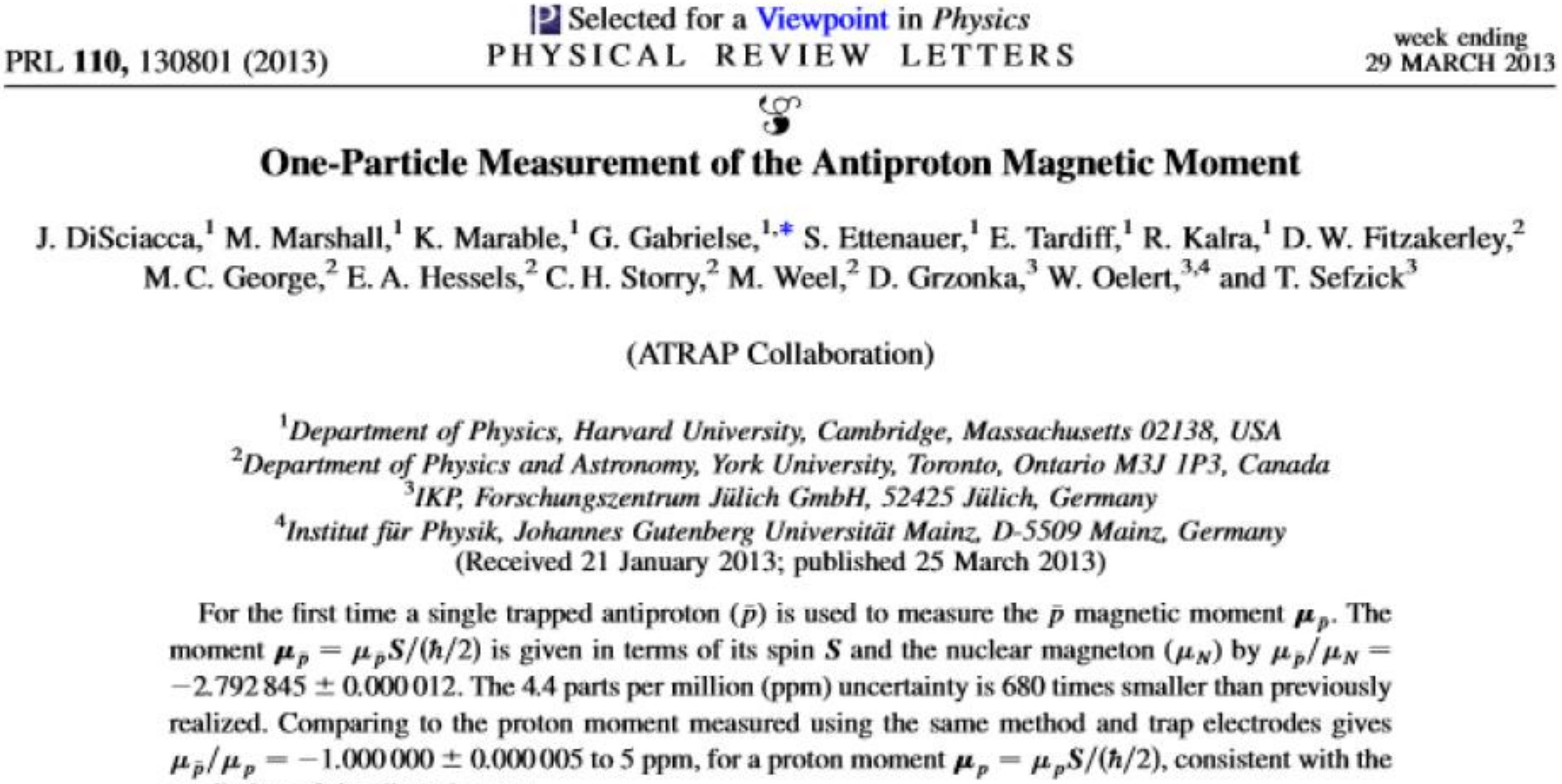
bottom

top

more precise measurements
will take place here

Located within a self-shielding superconducting solenoid
→ we invented in part to deal with magnetic noise at CERN

680 Times Improved Pbar to P Comparison



Selected for a Viewpoint in *Physics*
PRL **110**, 130801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

One-Particle Measurement of the Antiproton Magnetic Moment

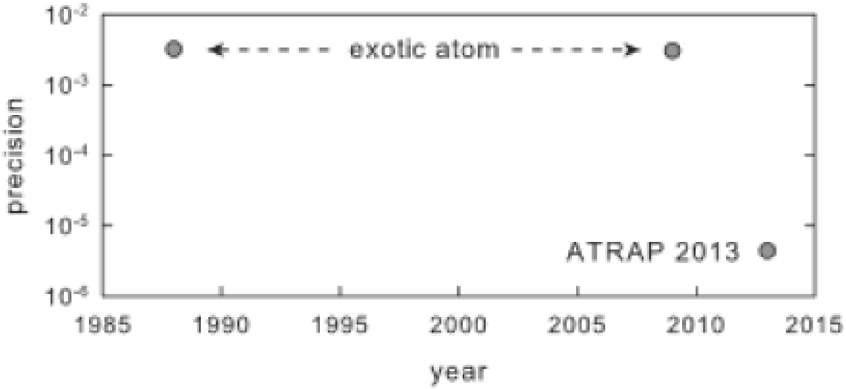
J. DiSciacca,[1] M. Marshall,[1] K. Marable,[1] G. Gabrielse,[1,*] S. Ettenauer,[1] E. Tardiff,[1] R. Kalra,[1] D. W. Fitzakerley,[2] M. C. George,[2] E. A. Hessels,[2] C. H. Storry,[2] M. Weel,[2] D. Grzonka,[3] W. Oelert,[3,4] and T. Sefzick[3]

(ATRAP Collaboration)

[1] *Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2] *Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada*
[3] *IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[4] *Institut für Physik, Johannes Gutenberg Universität Mainz, D-5509 Mainz, Germany*

(Received 21 January 2013; published 25 March 2013)

For the first time a single trapped antiproton ($\bar{p}$) is used to measure the $\bar{p}$ magnetic moment $\boldsymbol{\mu}_{\bar{p}}$. The moment $\boldsymbol{\mu}_{\bar{p}} = \mu_{\bar{p}} \boldsymbol{S}/(\hbar/2)$ is given in terms of its spin $\boldsymbol{S}$ and the nuclear magneton (μ_N) by $\mu_{\bar{p}}/\mu_N = -2.792\,845 \pm 0.000\,012$. The 4.4 parts per million (ppm) uncertainty is 680 times smaller than previously realized. Comparing to the proton moment measured using the same method and trap electrodes gives $\mu_{\bar{p}}/\mu_p = -1.000\,000 \pm 0.000\,005$ to 5 ppm, for a proton moment $\boldsymbol{\mu}_p = \mu_p \boldsymbol{S}/(\hbar/2)$, consistent with the prediction of the *CPT* theorem.



$$\mu_{\bar{p}}/\mu_p = -1.000\,000 \pm 0.000\,005 \qquad [5.1\ \text{ppm}],$$

$$\mu_{\bar{p}}/\mu_p = -0.9999992 \pm 0.0000044 \quad [4.4\,\text{ppm}],$$

Comparing to Other CPT Tests

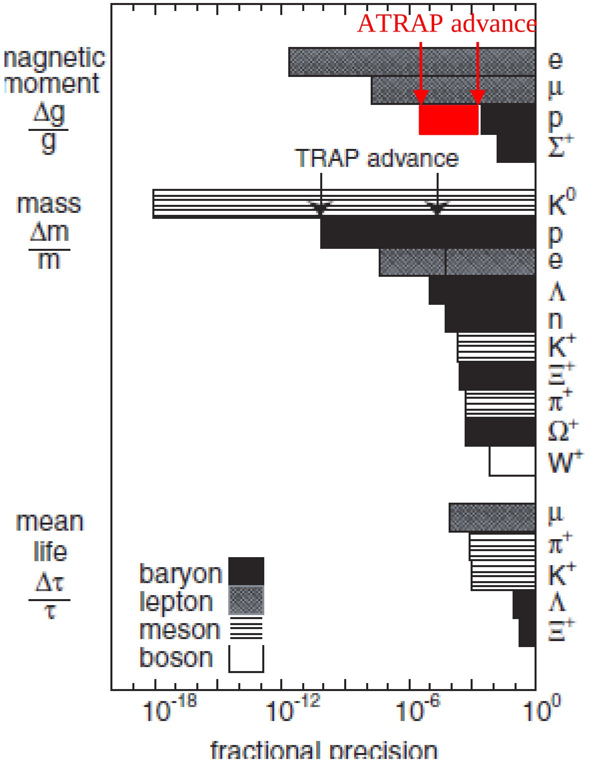


Figure 1: CPT Tests (primarily from the Particle Data Group compilation). Charge-to-mass ratio comparisons are included in "mass" measurements.

- Already one of the most precise antimatter-matter comparisons
- Will be one of the most precise tests if we improve by an additional 1000 to 10,000

Stringent Low Energy Tests of the Standard Model and Its Symmetries

Illustrate with experiments that have 3 kinds of objectives

1. Testing the Standard Model's most precise prediction
   by making the most precise measurement
   of a property of an elementary particle

   electron magnetic dipole moment

2. Testing very different predictions of the Standard Model
   and Supersymmetry (and other) models

   electron electric dipole moment

   also neutron, proton, Hg

3. Testing the most fundamental symmetry of the Standard Model

   q/m for antiproton and proton

   mag. moments of e^+ and e^-

Electron Electric Dipole Moment

- A most precise test of extensions to the standard model
- 12 times more precise than previous measurements

Magnetic moment: $\vec{\mu} = \mu \dfrac{\vec{S}}{\hbar / 2}$

Well measured
(just reviewed)

Electric dipole moment: $\vec{d} = d \dfrac{\vec{S}}{\hbar / 2}$

Does this also exist?
Why is it interesting?

12-Fold More Sensitive Measurement of the Electron Electric Dipole Moment

Gerald Gabrielse
Leverett Professor Physics, Harvard University

Advanced **C**old **M**olecule **E**DM


ACME Collaboration: Jacob Baron, Wesley C. Campbell, David DeMille, John M. Doyle, Gerald Gabrielse, Yulia V. Gurevich, Paul W. Hess, Nicholas R. Hutzler, Emil Kirilov, Ivan Kozyryev, Brendon R. O'Leary, Cristian D. Panda, Maxwell F. Parsons, Elizabeth S. Petrik, Ben Spaun, Amar C. Vutha, Adam D. West

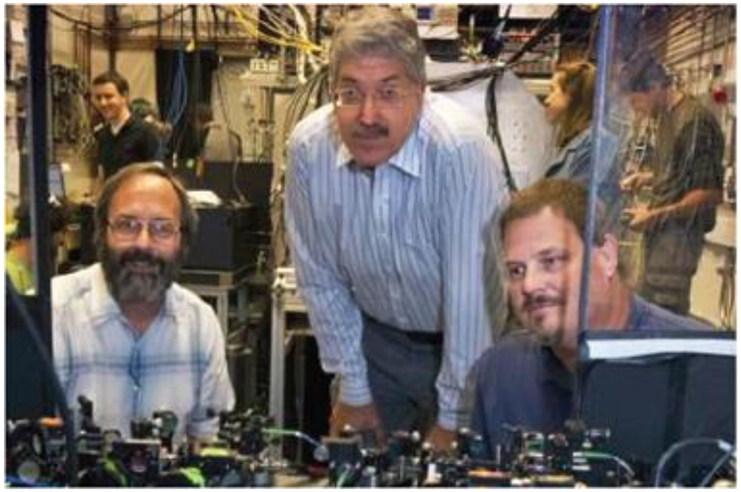
Science **343**, 269 (2014)

NSF, and NIST

ACME Collaboration

Joint effort of
3 research groups

Gerald
Gabrielse
(Harvard)



David
DeMille
(Yale)

John Doyle (Harvard)

ACME
PhD

Ben Spaun Chris Panda Nick Hutzler

Adam West

Brendon O'Leary Paul Hess Jacob Baron Elizabeth Petrik

Earlier: Amar Vutha, Yulia Gurevich, Emil Kirilov, Ivan Kozyreyv, Wes Campbell

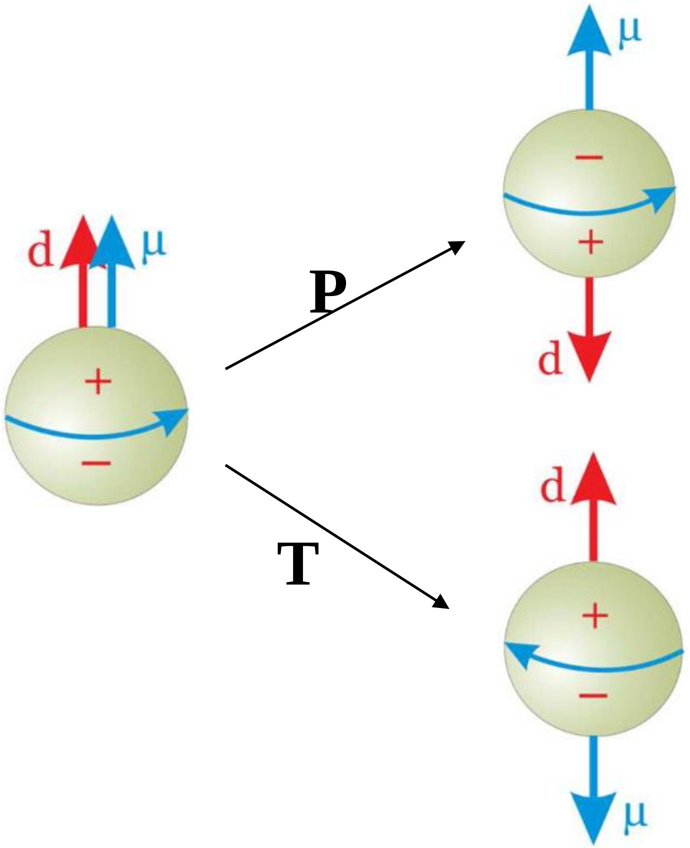
Particle EDM Requires Both P and T Violation

Magnetic moment:

$$\vec{\mu} = \mu \frac{\vec{S}}{\hbar/2}$$

Electric dipole Moment:

$$\vec{d} = d \frac{\vec{S}}{\hbar/2}$$



If reality is invariant under parity transformations **P**

→ **d = 0**

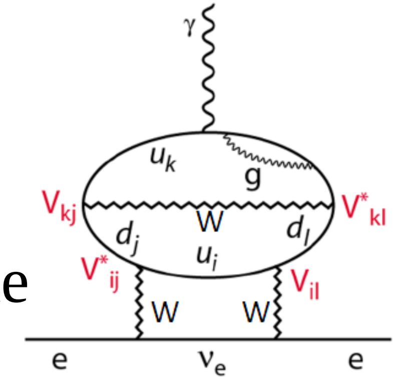
If reality is invariant under time reversal transformations **T**

→ **d = 0**

Standard Model of Particle Physics Predicts a Non-zero Electron EDM

Standard model: d ~ 10^{-38} e-cm

Too small to measure by orders of magnitude
best measurement: d ~ 2 x 10^{-27} e-cm



four-loop
level in
perturbati
theory

M. Pospelov and I. B. Khriplovich, "Electric dipole moment of the W boson and the electron in the Kobayashi-Maskawa model," Sov. J. Nucl. Phys. **53**, 638–640 (1991).

Weak interaction couples quark pairs (generations) $\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \begin{pmatrix} t \\ b' \end{pmatrix}$

CKM matrix relates to d, s, b quarks
(Cabibbo-Kabayashi-Maskawa matrix)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

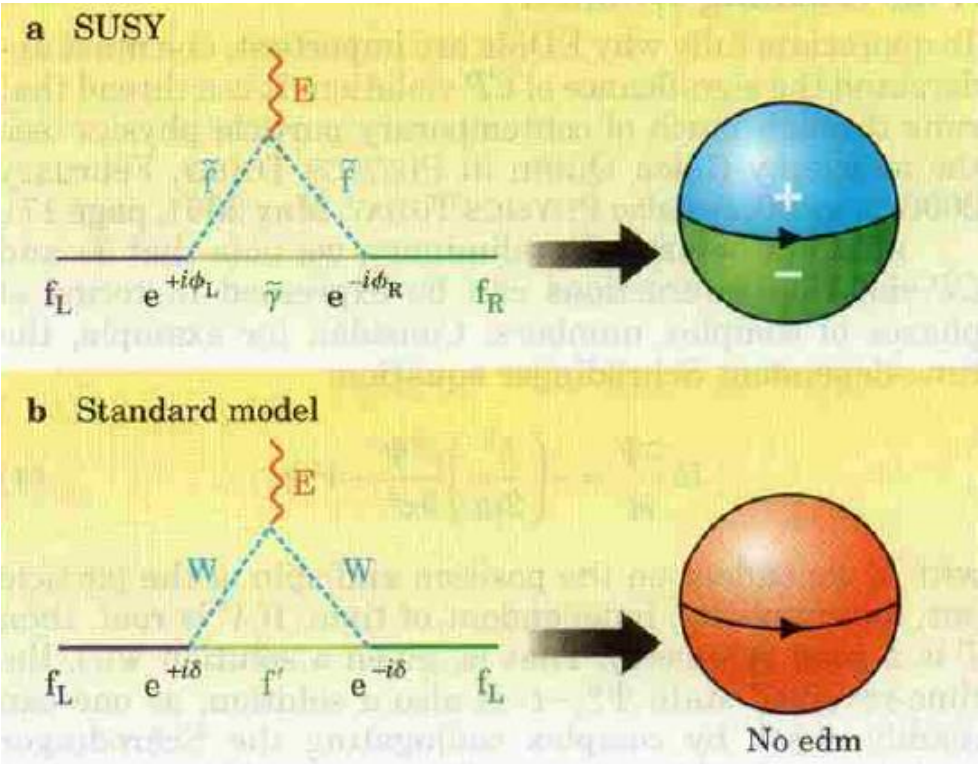
$$\downarrow$$

almost the unit matrix

$$\begin{pmatrix} 0.974 & 0.227 & 0.004 \\ 0.227 & 0.973 & 0.042 \\ 0.008 & 0.042 & 0.999 \end{pmatrix}$$

Extensions to the Standard Model
→ Much Bigger, Measureable Electron EDM

An example

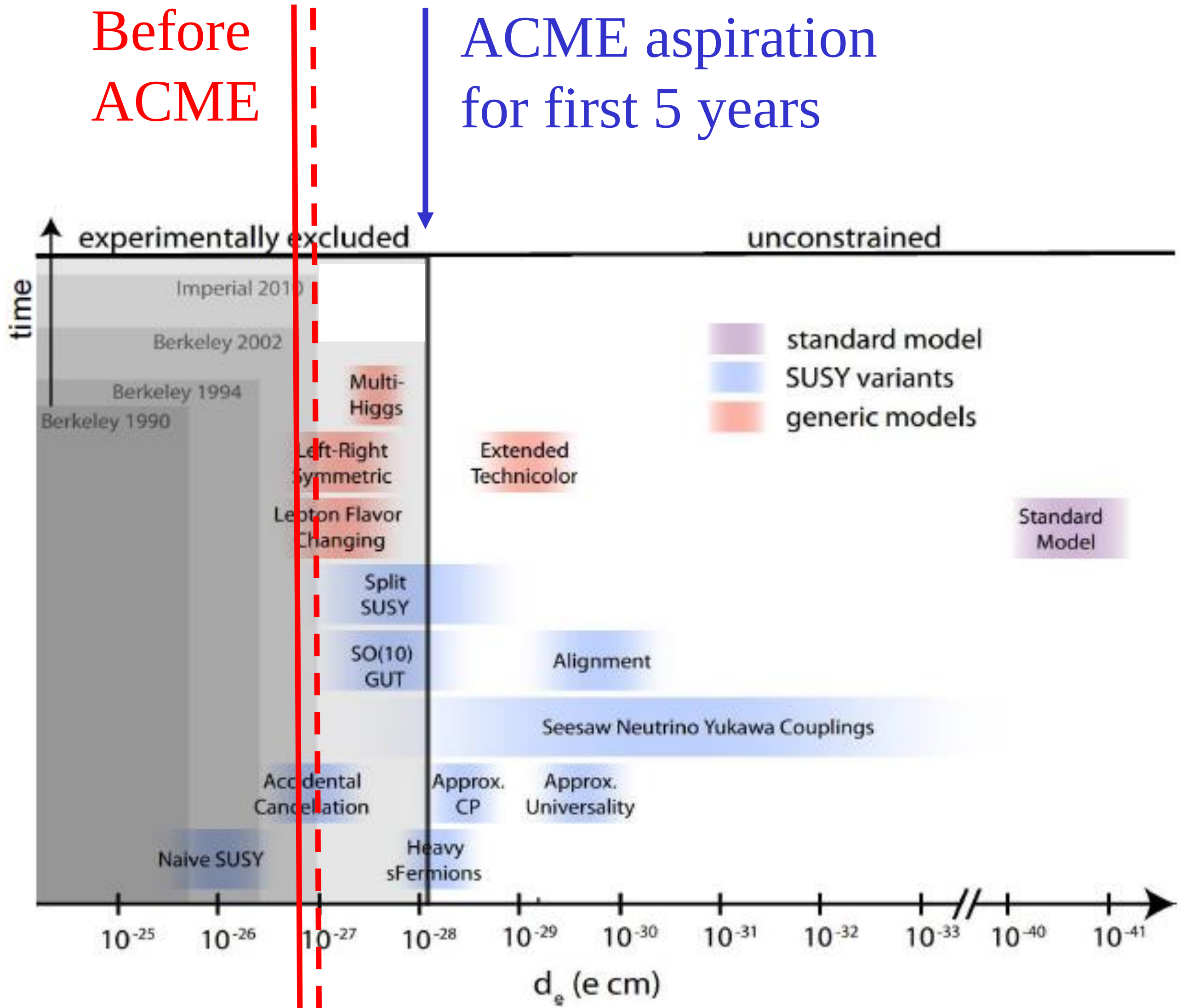


Low order contribution
→ larger moment

Low order contribution
→ vanishes

From Fortson, Sandars and Barr, Physics Today, 33 (June 2003)

Before Our ACME Measurement of Electron EDM



Before ACME

ACME aspiration for first 5 years

W. Bernreuther, M. Suzuki, *Rev. Mod. Phys*. **63**, 313 (1991)

Before ACME: No Particle EDM Had Yet Been Detected

Electron EDM limit $$|d_e| \leq 1.6 \times 10^{-27} e \text{ cm}$$

Commins, …
PRL **88**, 071805 (2002)

1.0 Hinds, 2011

Neutron EDM limit $$|d_n| < 2.9 \times 10^{-26} e \text{ cm}$$

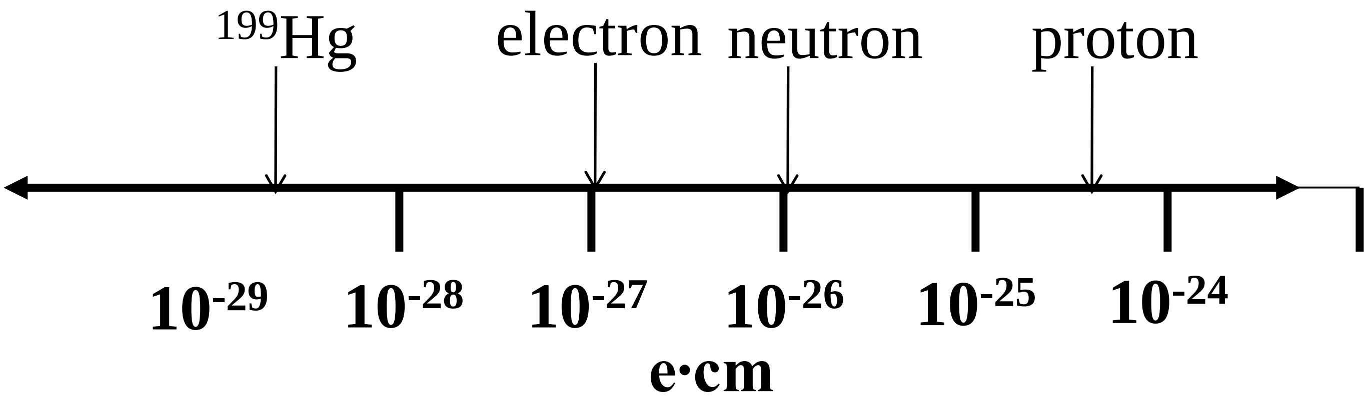
IIL Grenoble,
PRL **97**, 131801 (2006)

Proton EDM limit $$|d_p| < 7.9 \times 10^{-25} \ e \text{ cm}$$

Heckel, Fortson, …
PRL **102**, 101601 (2009)

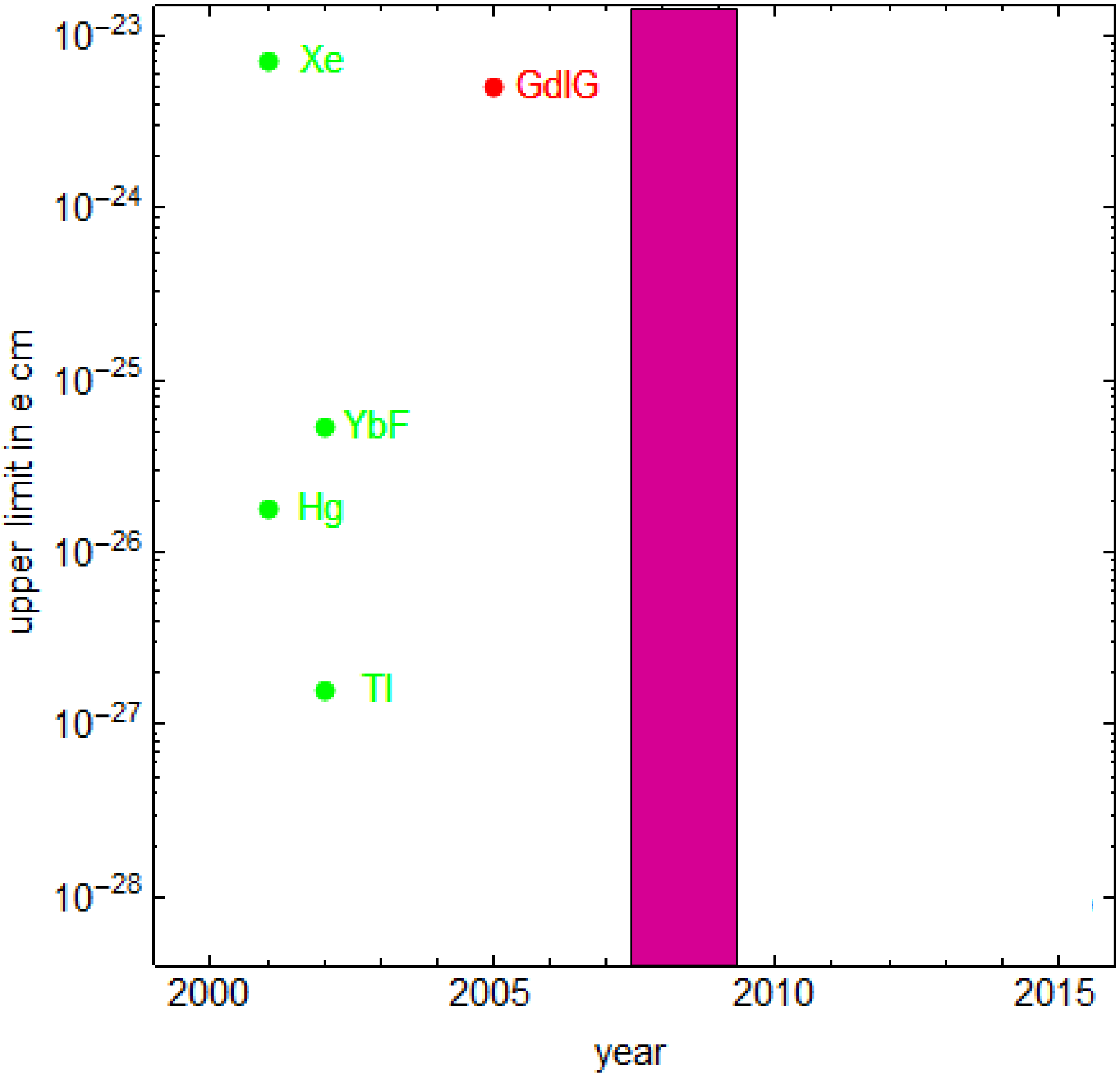
from $|d({}^{199}\mathrm{Hg})| < 3.1 \times 10^{-29} \ e \text{ cm}$

also sets $|d_n| < 5.8 \times 10^{-26} \ e \text{ cm}$



Electron EDM Measurements Before ACME

ACME started 2007 - 2009



There had not been new EDM reports in some Years

The LHC was soon to start testing the standard model

How to Measure an Electron EDM

Put the EDM in an Electric Field

bigger is better

$$H = -\vec{d} \bullet \vec{E}$$

Measure the energy shift for the system

Cannot Use Electric Field Directly on an Electron or Proton

Electric field would accelerate an electron out of the apparatus

Simple E and B can be used for neutron EDM measurement
(neutron has magnetic moment but no net charge)

Electron EDM are done within atoms and molecules
(first molecular ion measurement is now being attempted)

Schiff Theorem – for Electron in an Atom or Molecule

Schiff (1963) – no atomic or molecular EDM (i.e. linear Stark effect)

- from electron edm
- nonrelativistic quantum mechanics limit

Sandars (1965) – can get atomic or molecular EDM (i.e. linear Stark effect)

- from electron edm
- relativistic quantum mechanics
- get significant enhancement for large Z

Commins, Jackson, DeMille (2007) – intuitive explanation Schiff

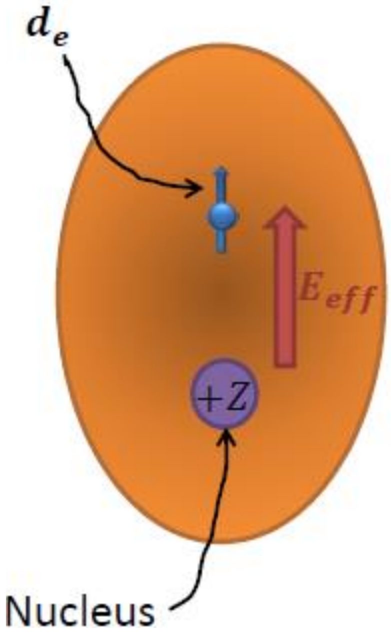
→ Lorentz contraction of the electron EDM in lab frame

Schiff, Phys. Rev. Lett. **132**, 2194 (1963);

Sandars, Phys. Rev. Lett. **14**, 194 (1965); *ibid* **22**, 290 (1966).

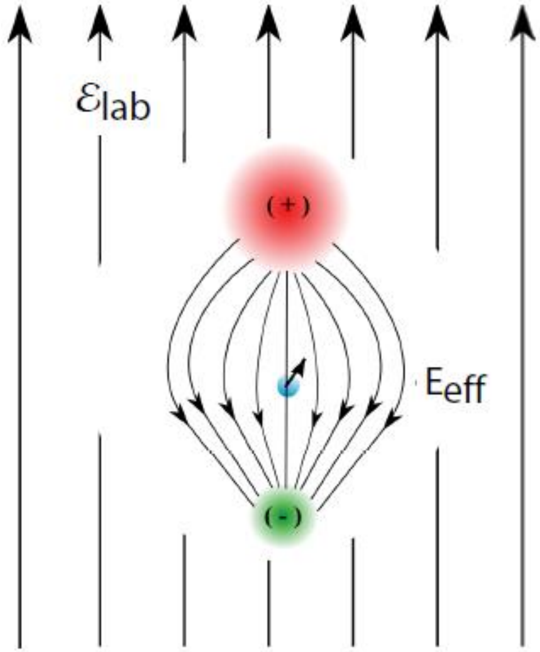
Commins, Jackson, DeMille, Am. J. Phys. **75**, 532 (2007).

Why Use a Molecule?
→ To Make Largest Possible Electric Field on Electron



Tl atom

$E_{lab} = 123\ \text{kV/cm} \quad \rightarrow \quad \text{E}_{eff} = 72\ \text{MV/cm}$

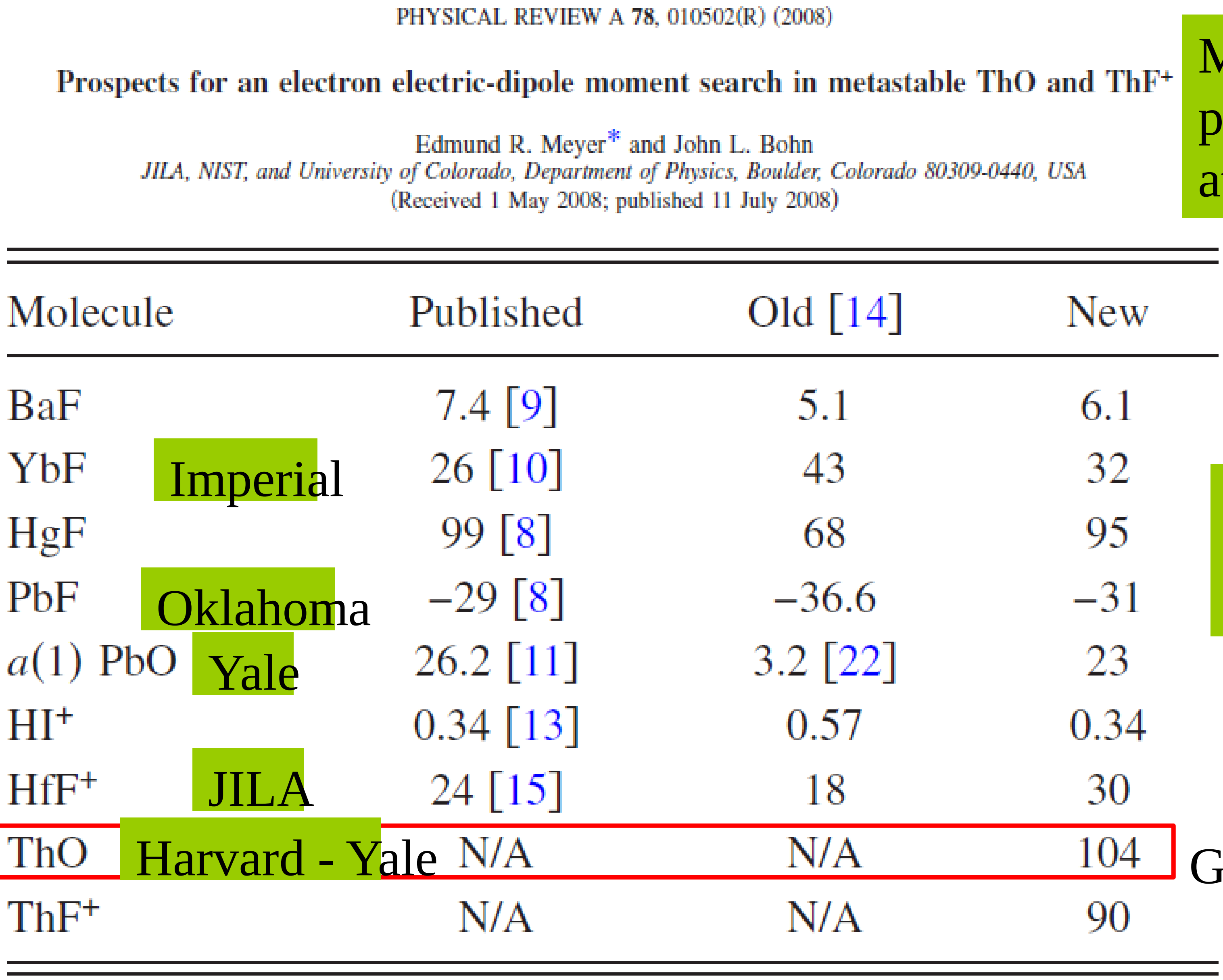


ThO molecule

$E_{lab} = 100\ \text{V/cm} \quad \rightarrow \quad \text{E}_{eff} = 100\ G\text{V/cm}$

Molecule can be more easily polarized using nearby energy levels with opposite parity (not generally available in atoms)

Promising Molecules



PHYSICAL REVIEW A 78, 010502(R) (2008)

Prospects for an electron electric-dipole moment search in metastable ThO and ThF$^+$

Edmund R. Meyer* and John L. Bohn
JILA, NIST, and University of Colorado, Department of Physics, Boulder, Colorado 80309-0440, USA
(Received 1 May 2008; published 11 July 2008)

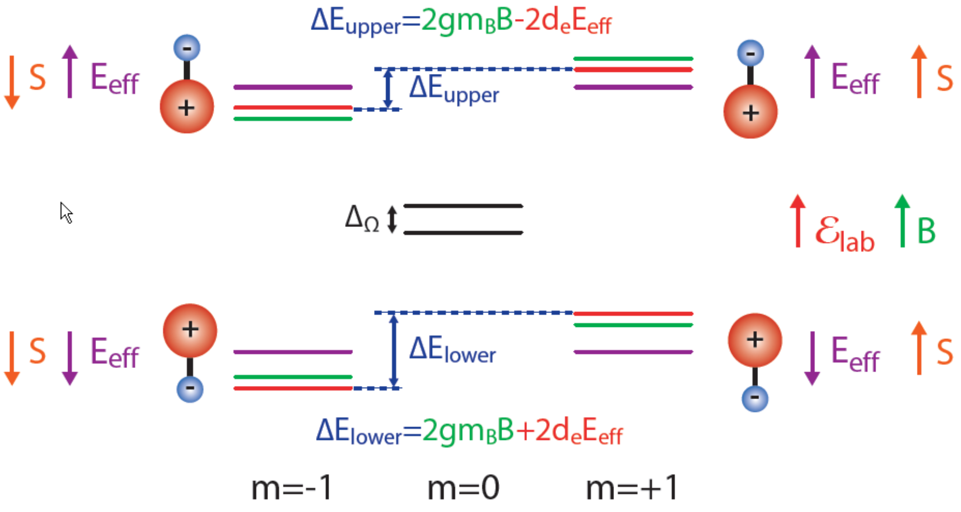
Molecule		Published	Old [14]	New
BaF		7.4 [9]	5.1	6.1
YbF	Imperial	26 [10]	43	32
HgF		99 [8]	68	95
PbF	Oklahoma	–29 [8]	–36.6	–31
a(1) PbO	Yale	26.2 [11]	3.2 [22]	23
HI$^+$		0.34 [13]	0.57	0.34
HfF$^+$	JILA	24 [15]	18	30
ThO	Harvard - Yale	N/A	N/A	104
ThF$^+$		N/A	N/A	90

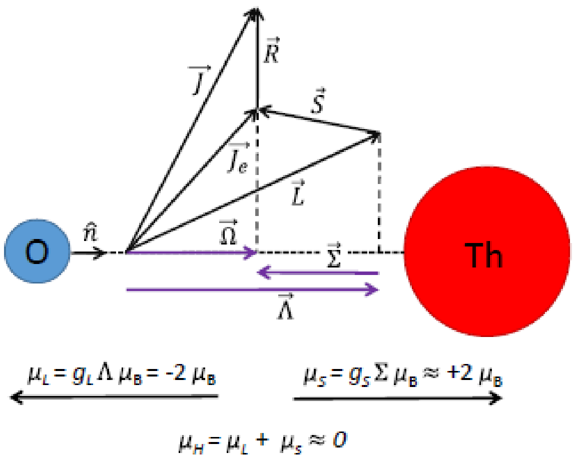
GV/cm

Molecular calc. project on atomic basis

Thallium atom Experiment used used 70 MV/cm high Z

ThO H Metastable State





Omega Doublet

- Nearly degenerate (300 kHz) opposite party)

$^3\Delta_1$

- Change internal field direction with no lab field change
- V/cm electric field saturates

Tiny magnetic moment

0.01 Bohr magnetons

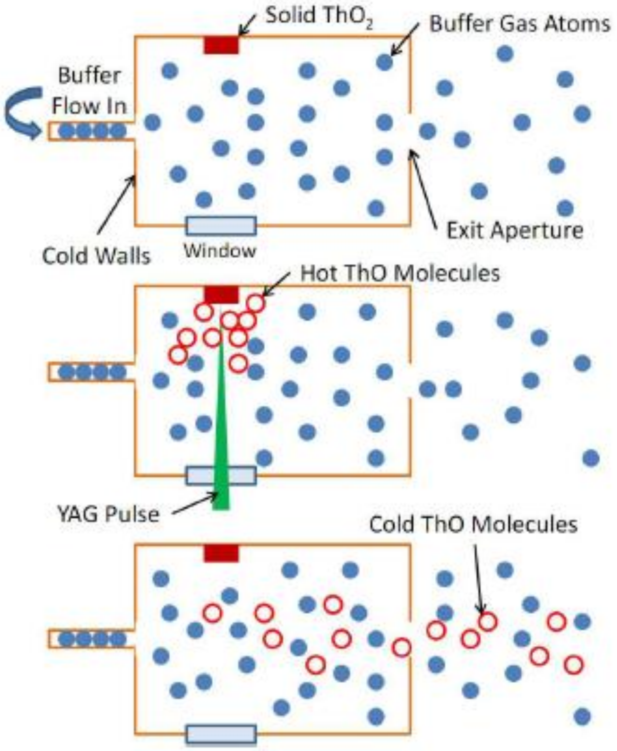
$^3\Delta_1$

long lived (> 1.8 ms)

diode lasers, TDA, fiber amplifiers

Disadvantage of ThO: Use an excited state

Solution: intense ablation source with Ne buffer gas cooling



ACME:	~10^{13} mol./state/sec use metastable state
Imperial:	~10^{10} mol./state/sec use ground state

ACME I and Imperial use about the same number of molecules for measurements

Specialty of the Doyle group:

*Hutzler *et al.* A cryogenic beam of refractory, chemically reactive molecules with expansion cooling. *PCCP* (2011).

Despite Huge Electric Field the EDM Gives Tiny Shift of Energy Levels

$$\Delta E = 7\times 10^{-18}\ eV$$
$$= 7\times 10^{-27}\ GeV$$
$$= 7\times 10^{-30}\ TeV$$

2 mHz

Not able to resolve directly

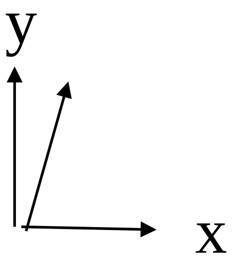
Example is for an electron edm equal the ACME upper limit.

Detect the Small Phase Shift

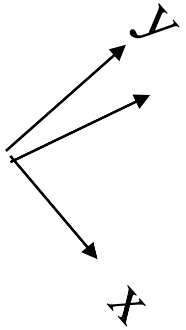
set by choice of dark state

set by choice of direction of the first of the two orthogonal detection laser polarizations

$$\frac{|m=1\rangle + e^{i\phi_o}|m=-1\rangle}{\sqrt{2}} \xrightarrow[\text{in E, B}]{\text{time}} \frac{|m=1\rangle + e^{i(\phi_o+\phi_1+\phi)}|m=-1\rangle}{\sqrt{2}}$$



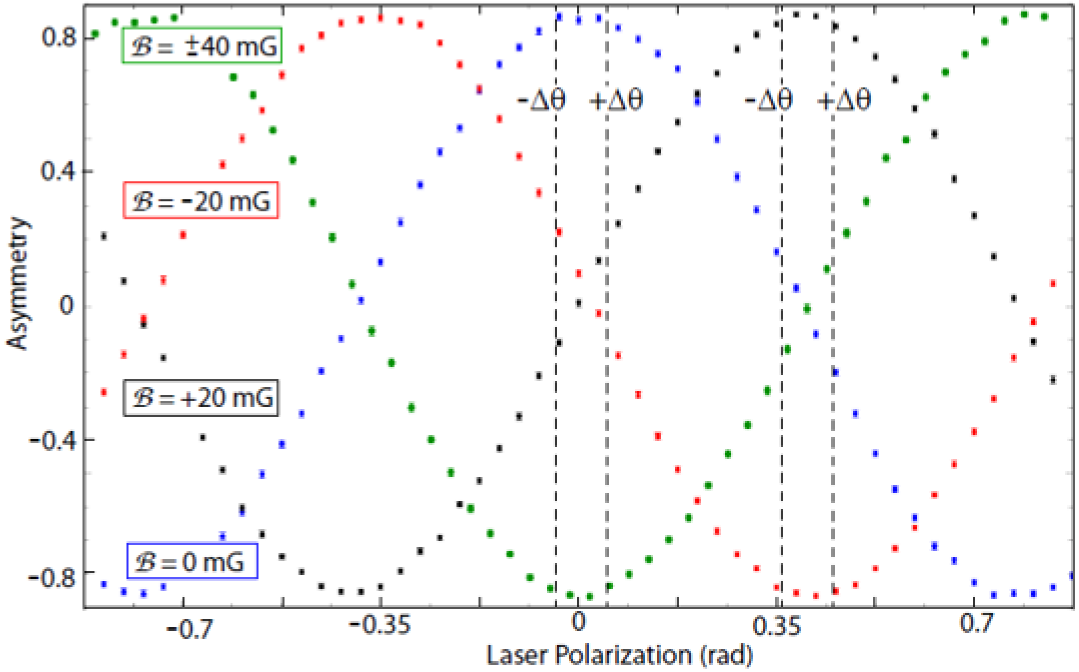
$$\phi \propto (\mu B + d E)\tau$$



$$T = 1.1ms \;\rightarrow\; \phi = 11\times 10^{-6} \;=\; 0.6\times 10^{-3}\text{ degrees}$$

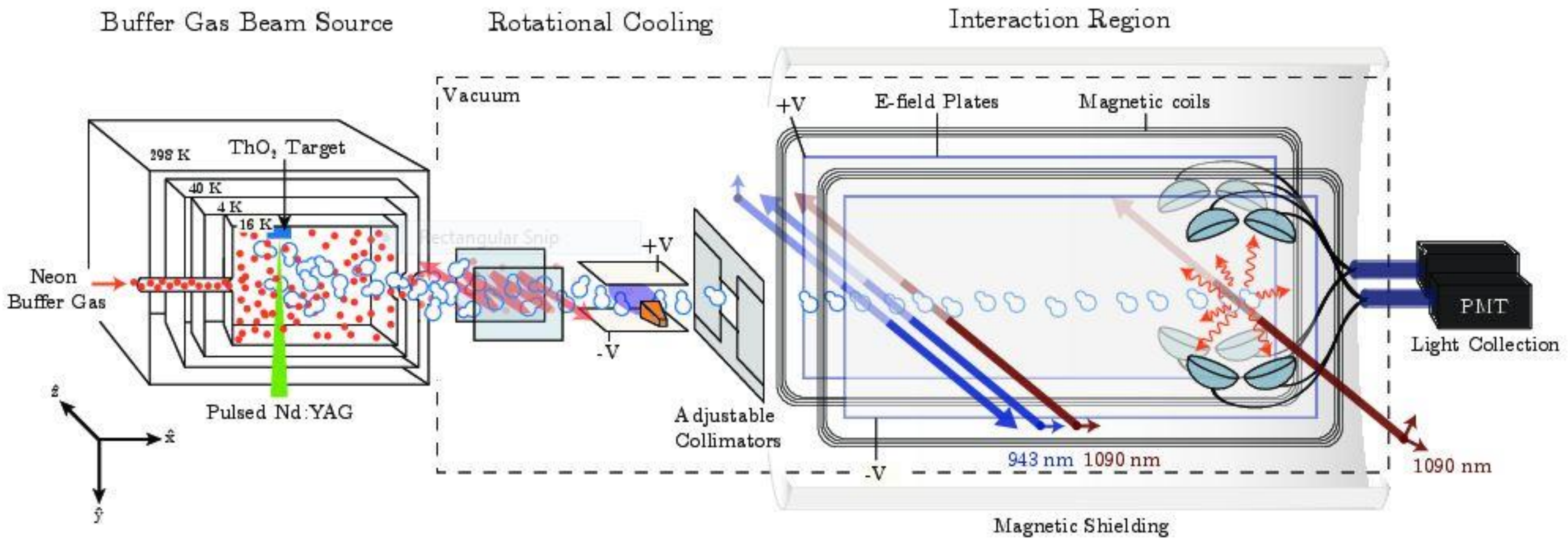
Example is for an electron edm equal the ACME upper limit.

Observed Fringes

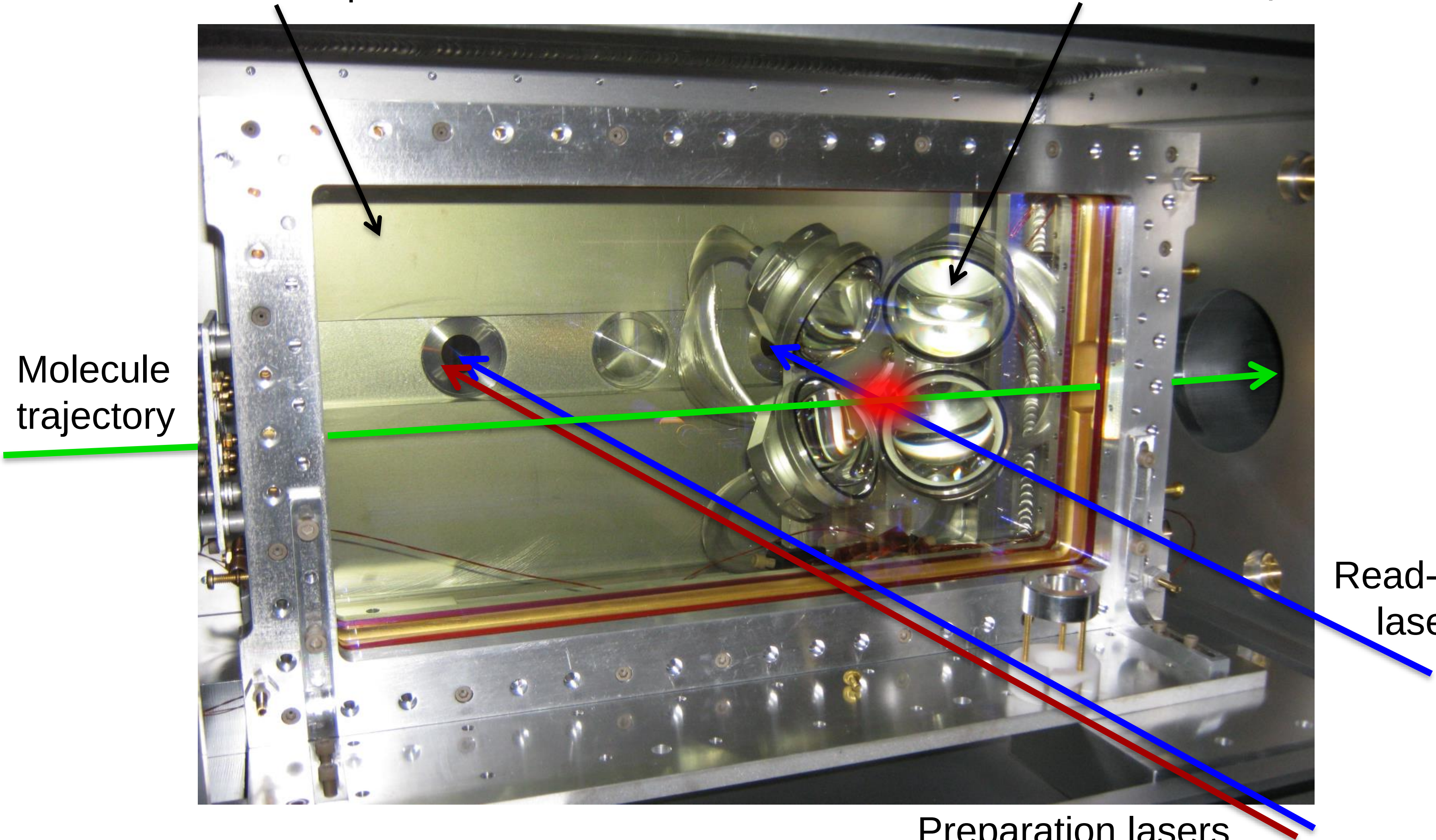


Sit on zero crossing to maximize phase sensitivity

Schematic of Experiment



Pump -- Evolve in E, B -- Probe



Glass *E*-field plates, ITO-coated

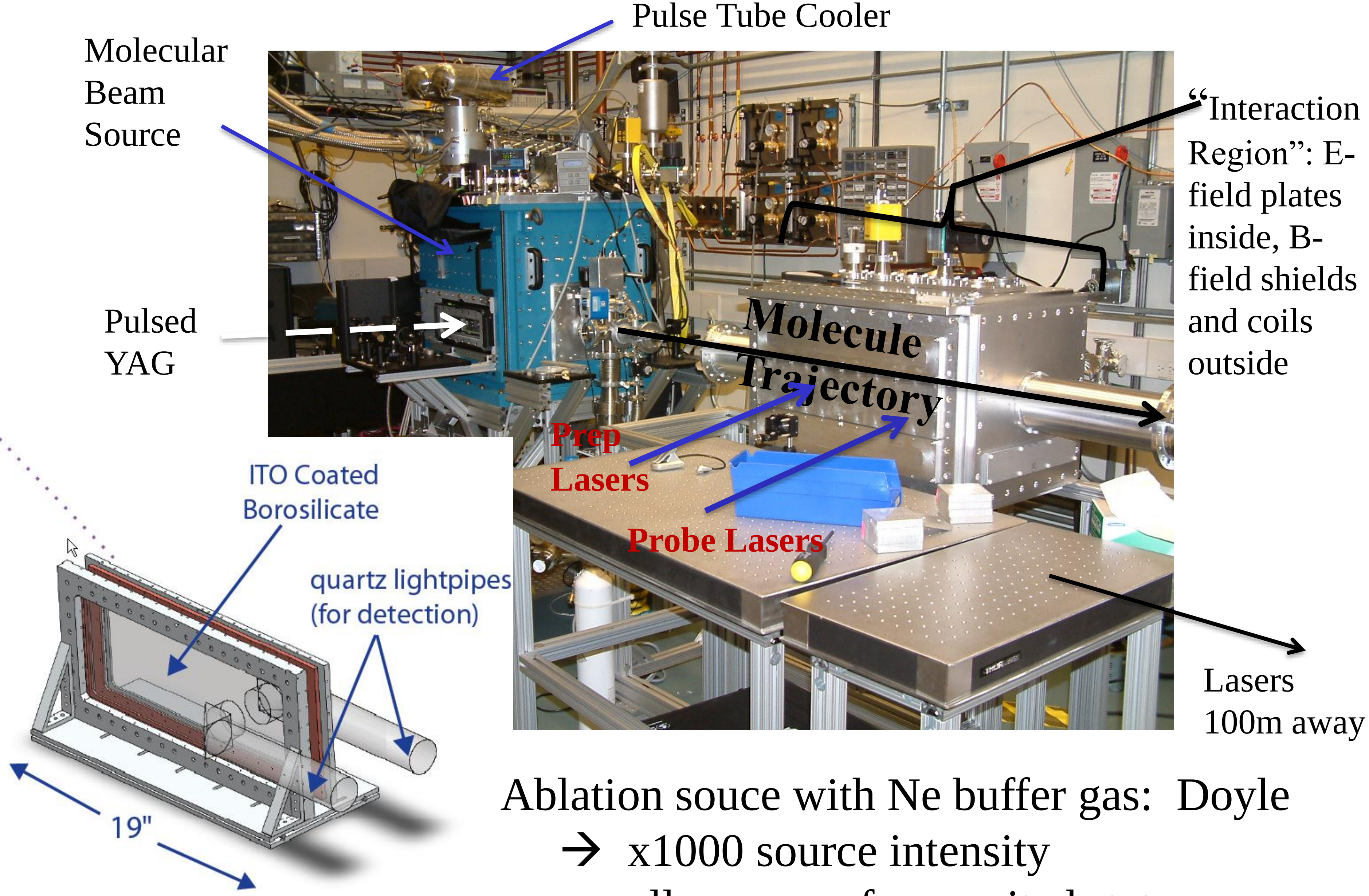
Fluorescence collection optics

Molecule trajectory

Read-out laser

Preparation lasers

ThO Molecular Beam



Pulse Tube Cooler

Molecular Beam Source

Pulsed YAG

"Interaction Region": E-field plates inside, B-field shields and coils outside

Molecule Trajectory

Prep Lasers

Probe Lasers

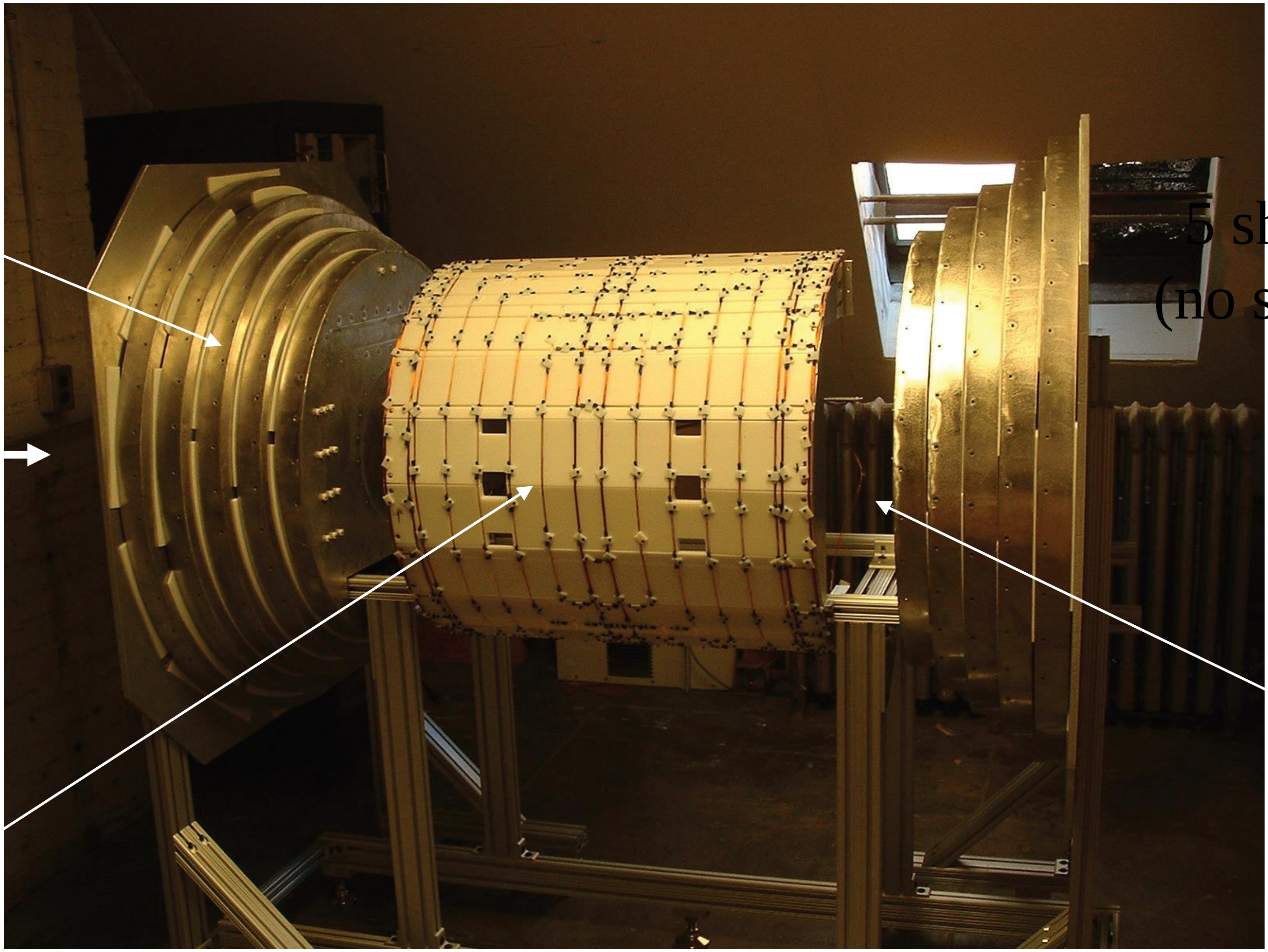
Lasers 100m away

Ablation souce with Ne buffer gas: Doyle

→ x1000 source intensity

allows use of an excited state

Magnetic Field Coils and Shielding



mu metal endplates

ThO beam

Cos(theta) coils to provide transverse B field

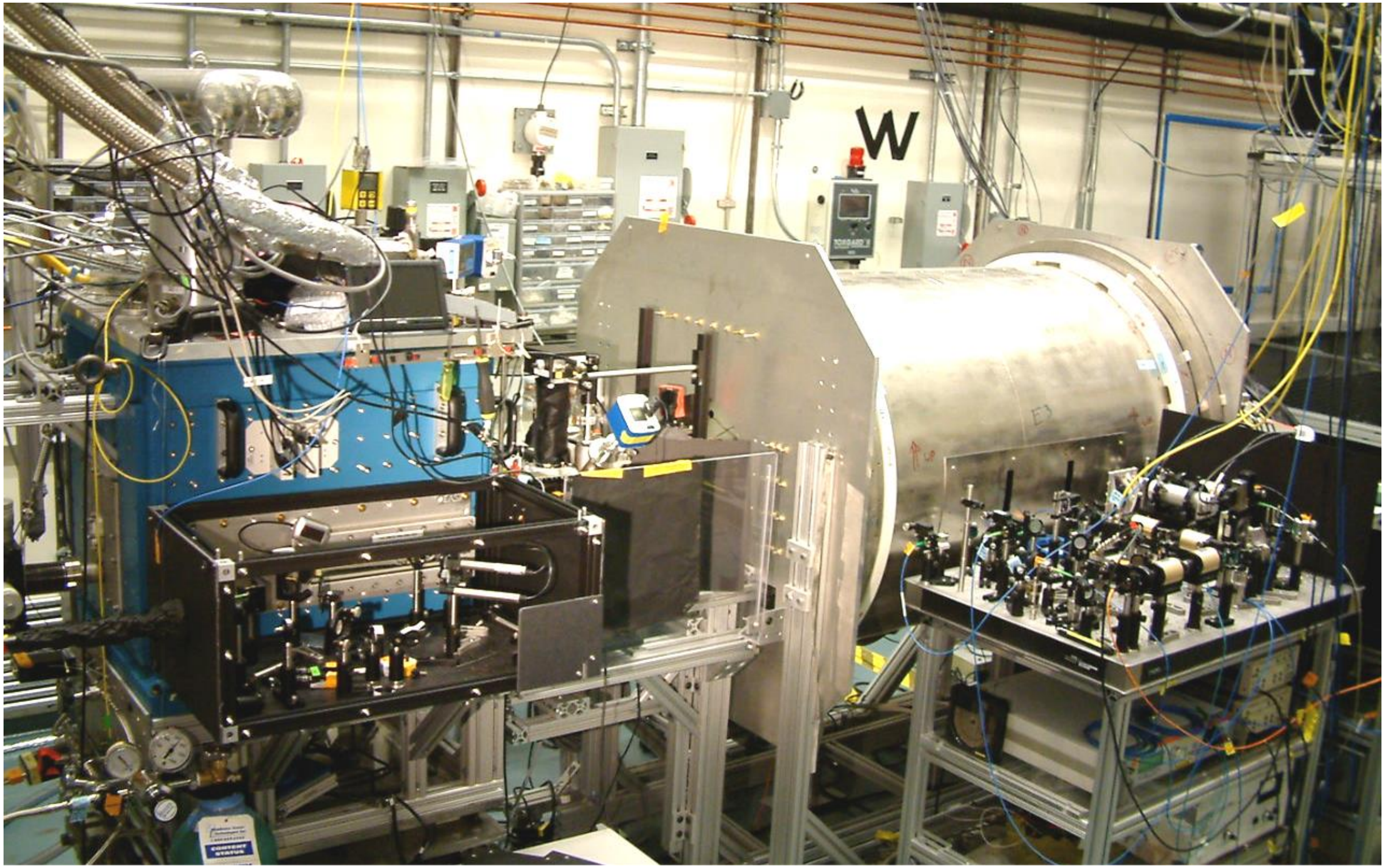
5 shields (no shown)

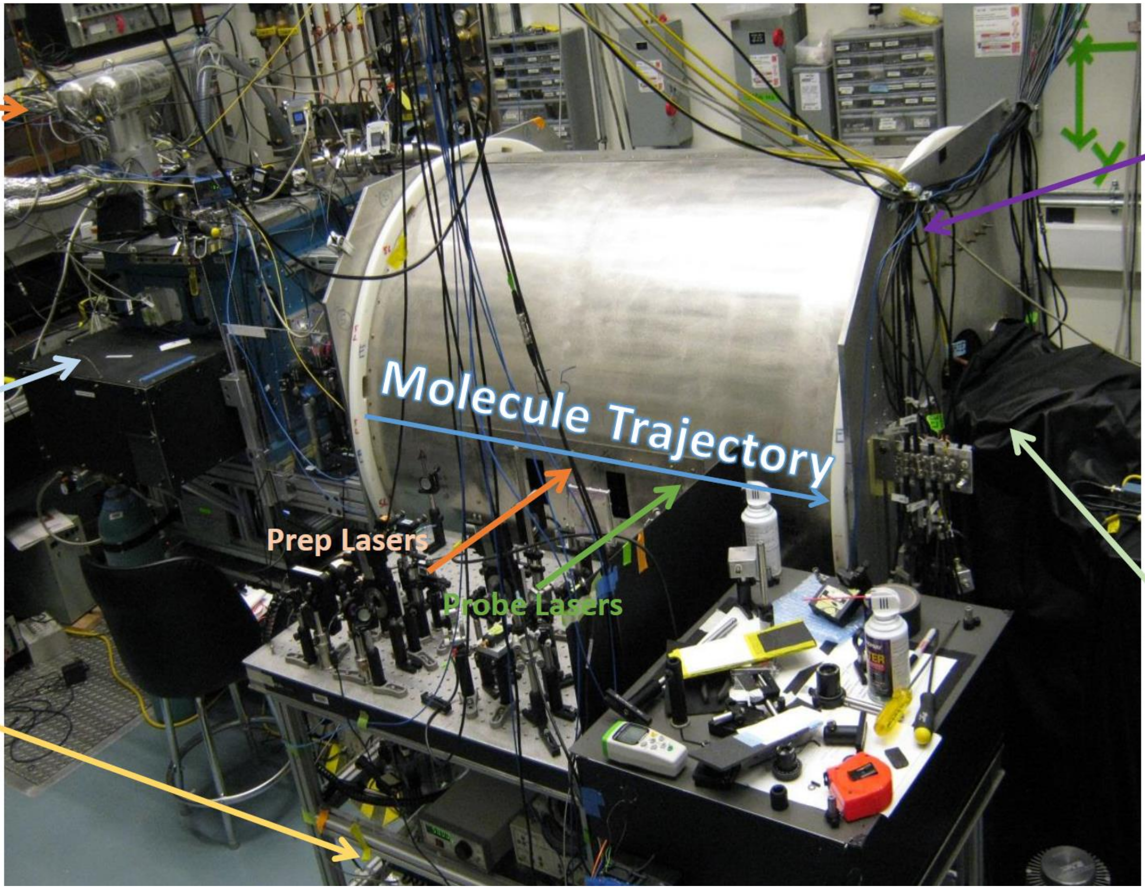
~ 10^{-5} shielding

Interaction chamber inside

200 mG with uniformity of 10^{-3} over 26 cm

Molecular Beam Apparatus





Pulse tube
Cryo
refrigerator

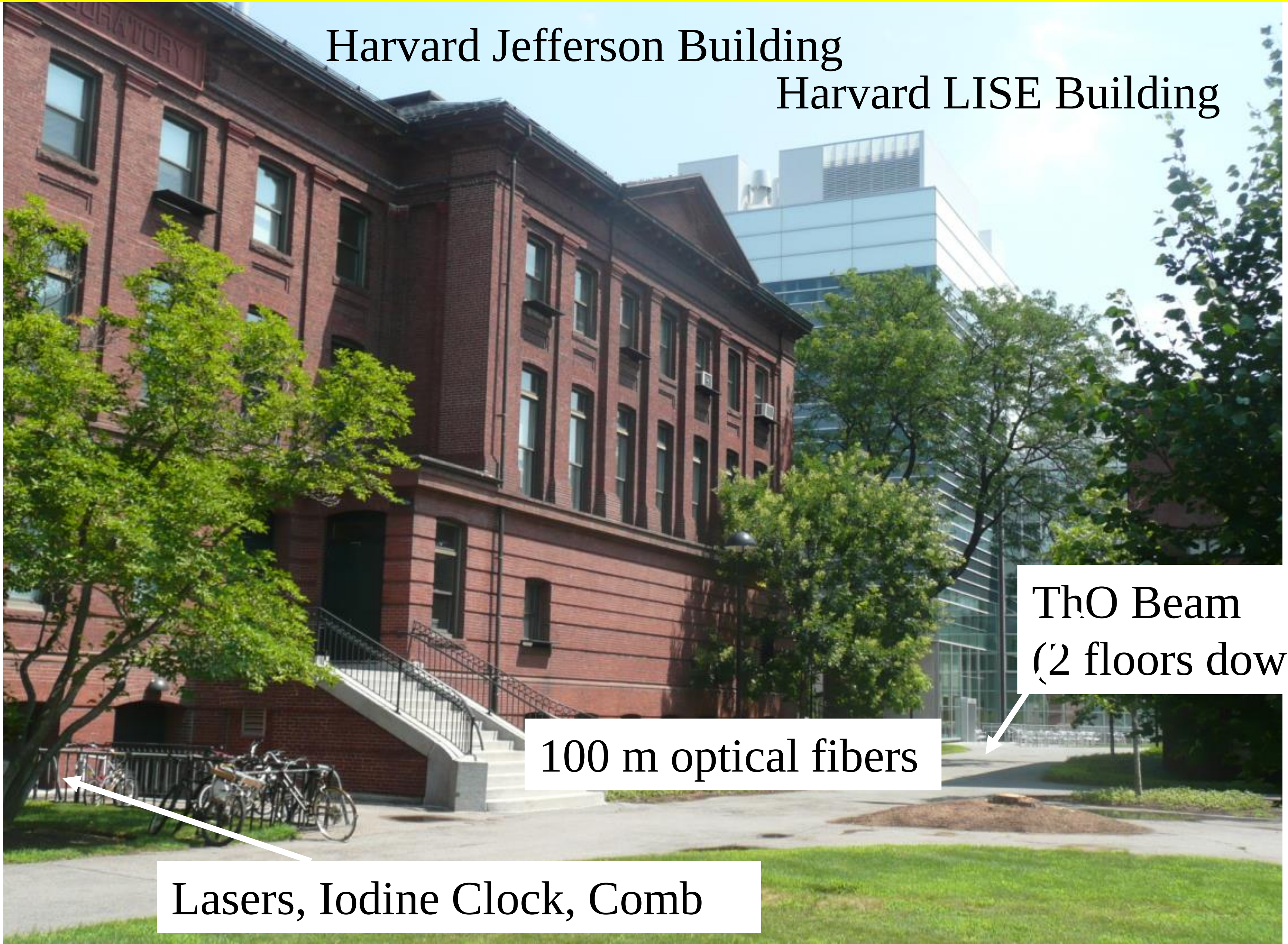
ThO Buffer
Gas Beam
source

Laser fiber
amplifier
(10 Watt)

5 layers of
mu-Metal
shields

PMTs for
detection

Lasers are 100 Meters Away



Harvard Jefferson Building

Harvard LISE Building

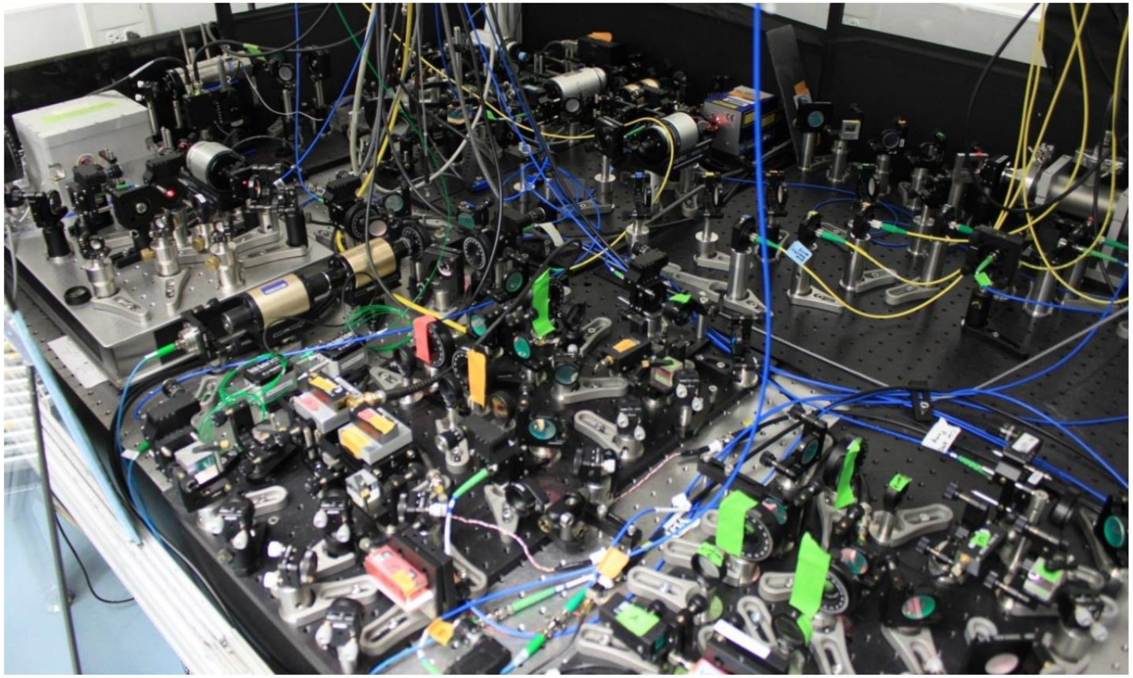
ThO Beam
(2 floors down)

100 m optical fibers

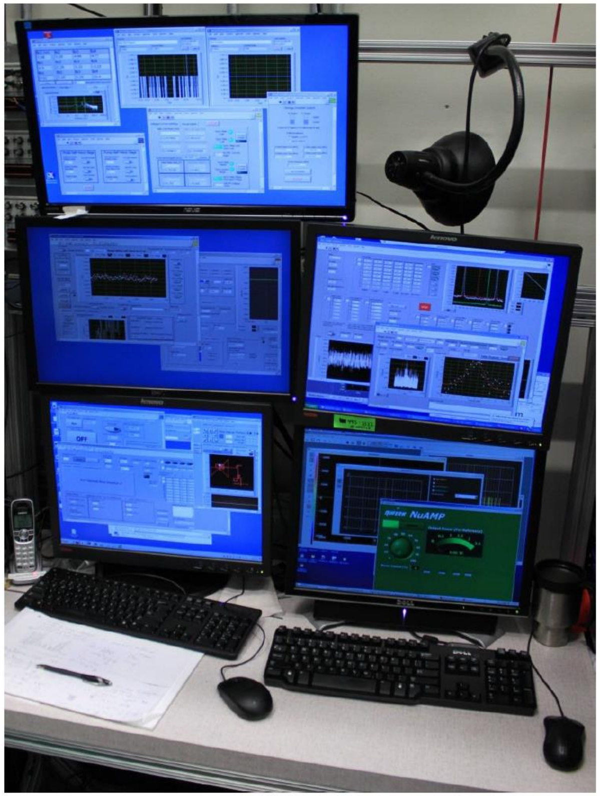
Lasers, Iodine Clock, Comb

Many Lasers

One of several optical tables w/ ~15 lasers total, modulators, locking electronics, fibers spanning across two buildings



“control room”



Fast polarization chopping

- Fluorescence signal is proportional to phase *and* molecule number:

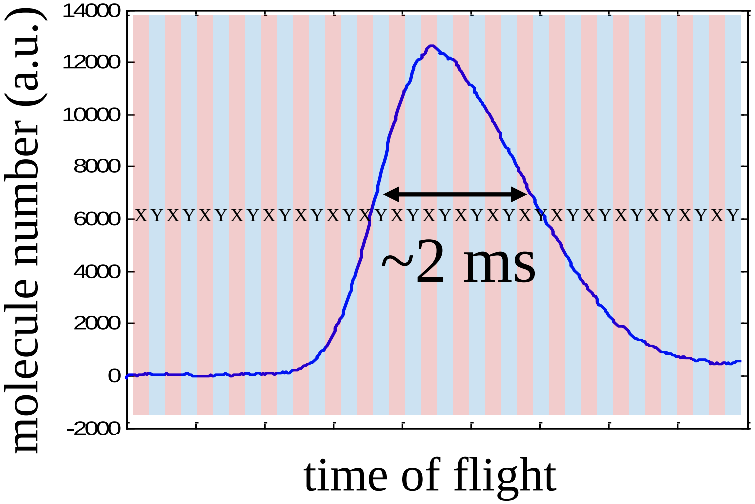
$$S_X = N_0 \sin^2(\phi)$$

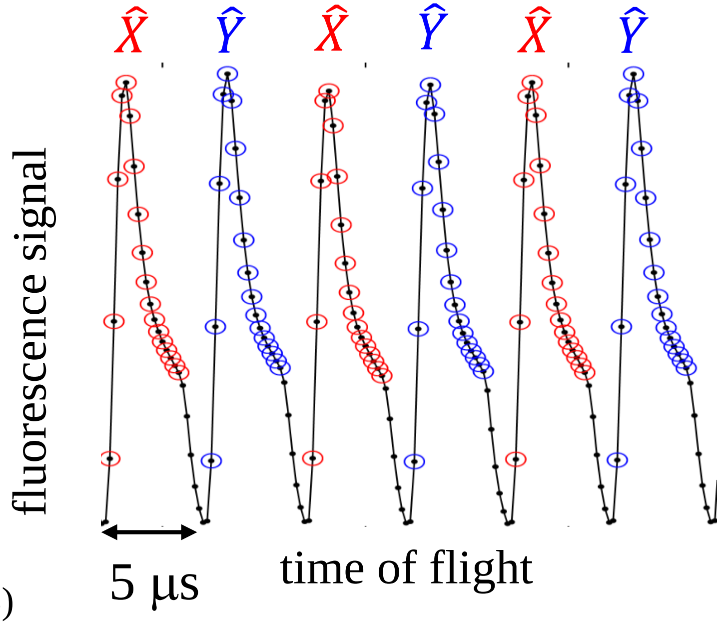
$$S_Y = N_0 \cos^2(\phi)$$

- Rapidly switch probe laser polarization
- Form asymmetry, which is immune to molecule number fluctuations:

$$A = \frac{S_Y - S_x}{S_Y + S_x} = \mathcal{C}\ \cos(2\phi)$$

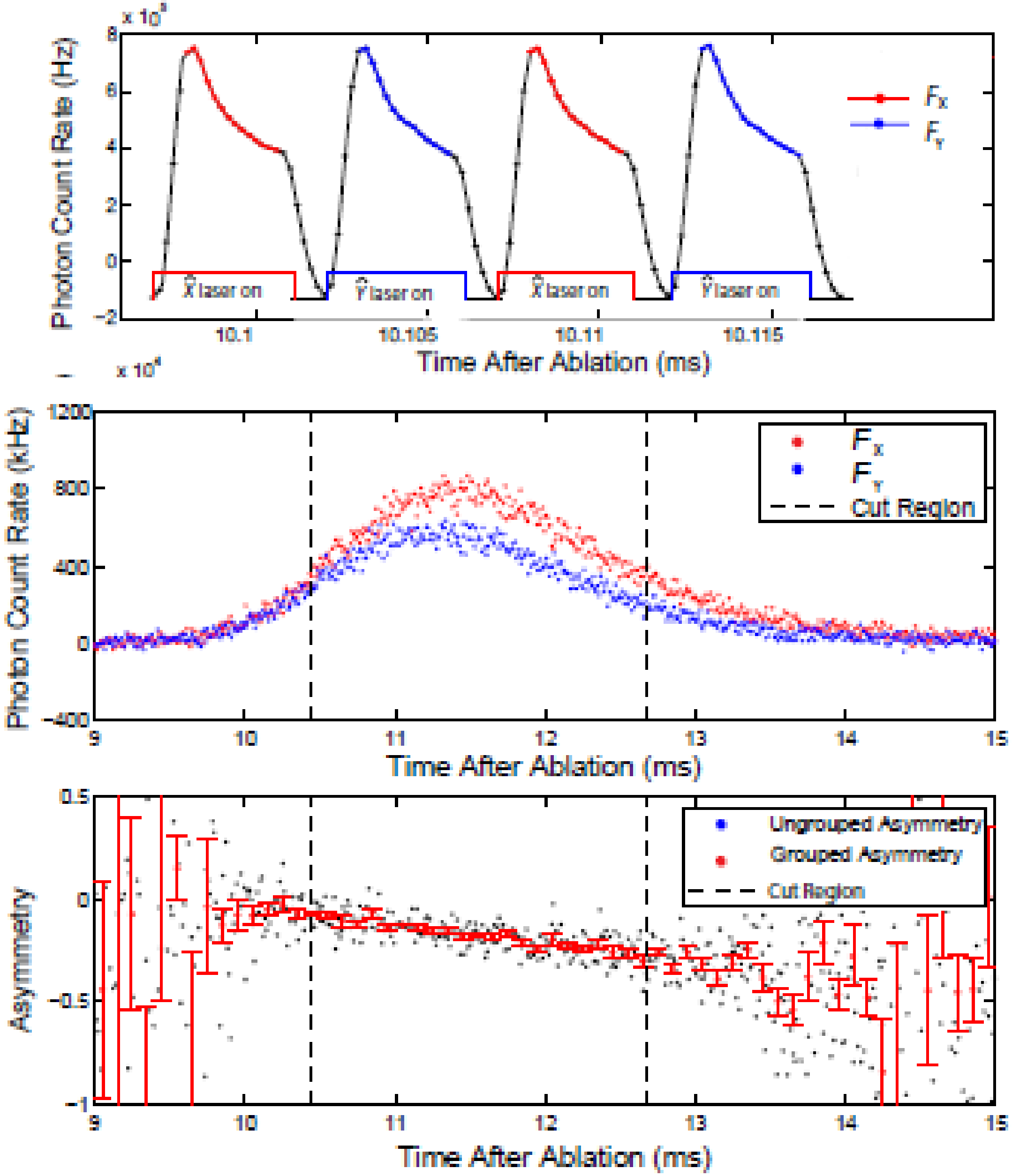
- Achieve shot-noise limited sensitivity.*





*E. Kirilov *et al*., PRA **88**, 013844 (2013)

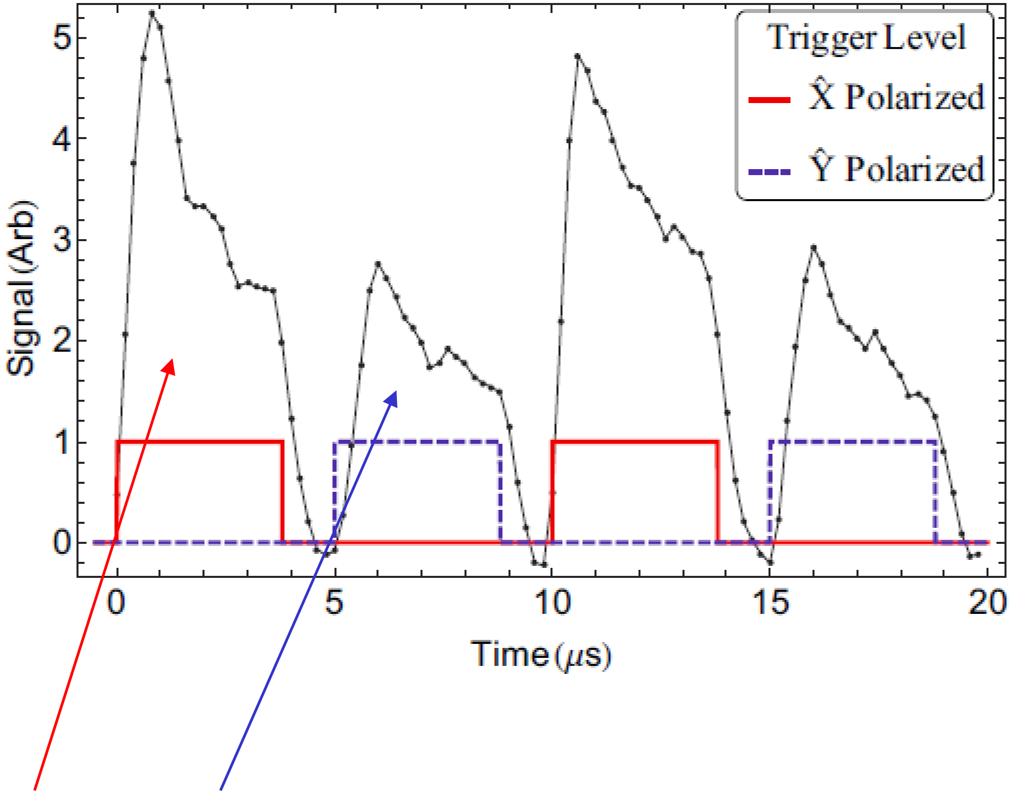
Fast Polarization Switching to Detect the Phase



$$A = \frac{S_X - S_Y}{S_X + S_Y}$$

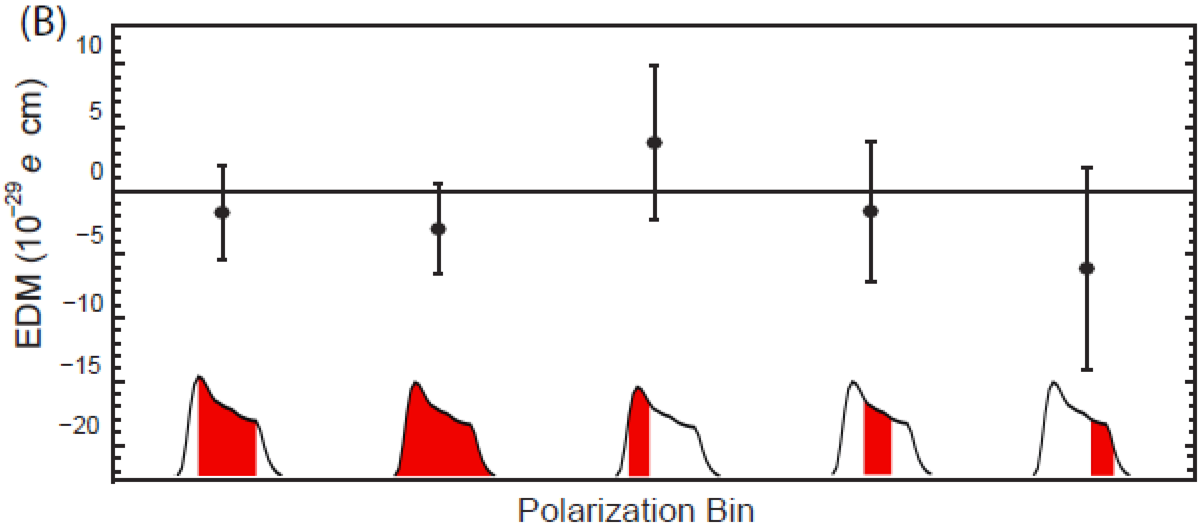
$$= C\ \cos(\phi_0 + \phi_1 + \phi)$$

Detect Final Phase Using Two Linear Polarizations



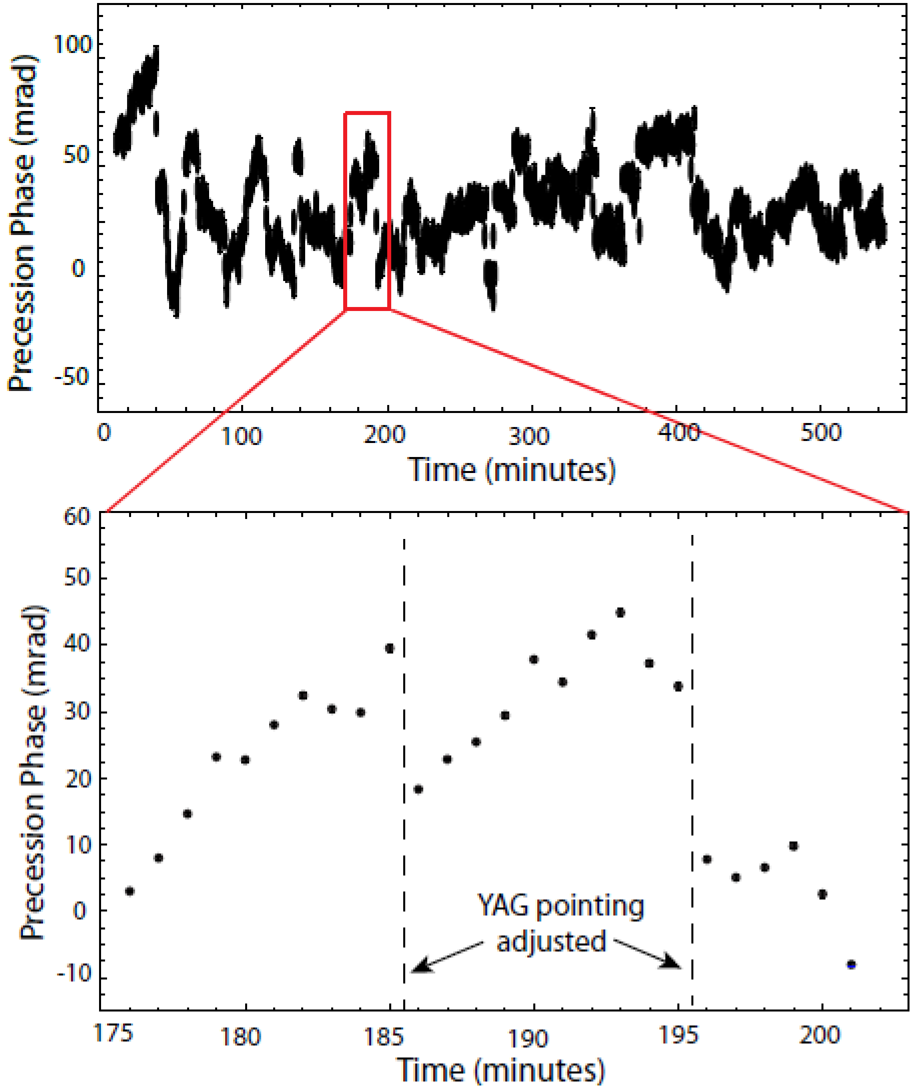
$$A = \frac{S_X - S_Y}{S_X + S_Y} = C\cos(\phi_0 + \phi_1 + \phi)$$

Integrate Over Various Times Intervals



Phase Slowly Drifts

as molecular velocity distribution changes

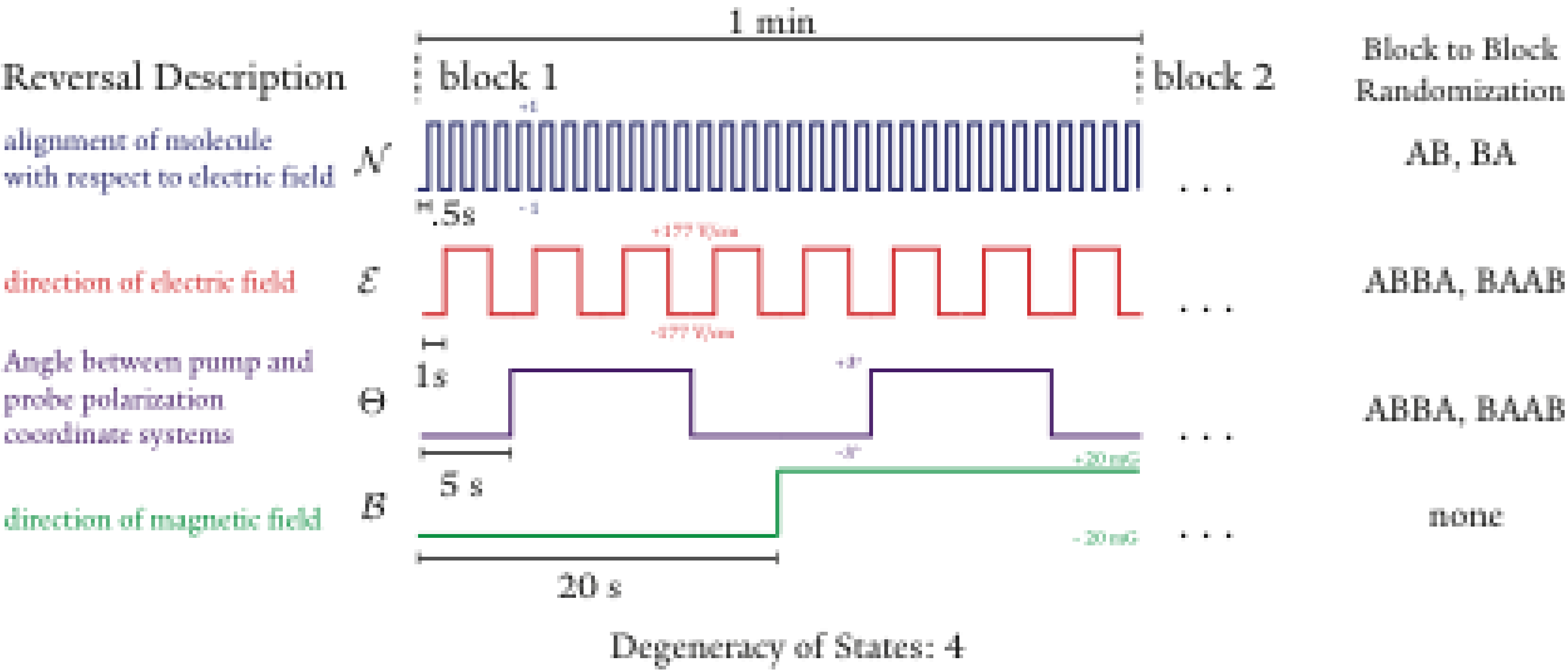


compare EDM

limit : 11 $\mu\, rad$

→ Look for much more rapid
In phase

Fast Switches



Minimize the time over which the beam, etc. could change

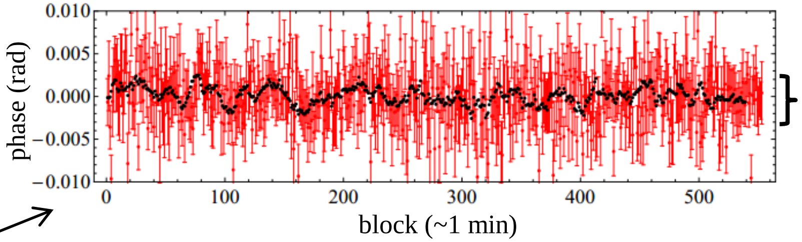
Measured Phase has Terms Linear in the Direction of N, E and B

internal electric field lab E field lab B field

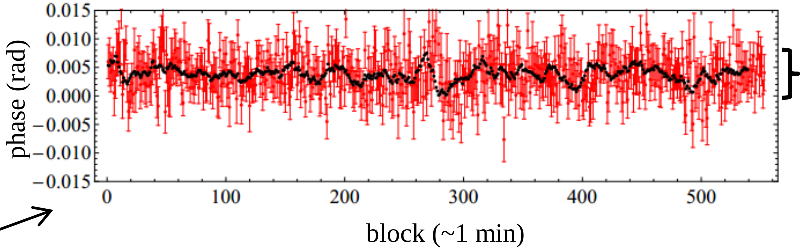
Parity sum (*N*•*E*•*B*)	**Derived quantities**
+ + +	$B_{nr}\ g\ \mu\ \tau + \theta_{nr}$
+ + -	$B_0\, g\ \mu\ \tau$
+ - +	$B_{leak}\, g\ \mu\ \tau$
+ - -	0
- + +	$B_{nr}\ \Delta g\ \mu\ \tau$
- + -	$B_0\ \Delta g\ \mu\ \tau$
- - +	$d_e\ E_{eff}\ \ \tau$
- - -	$B_0\ \ \eta\ E_{nr}\ \mu\ \tau$

single block

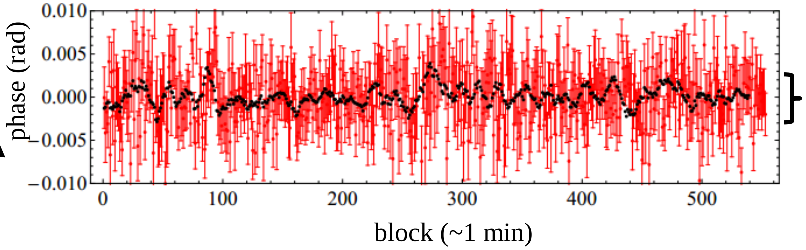
10 blocks averaged



3 ± 5 x 10^{-5} rad



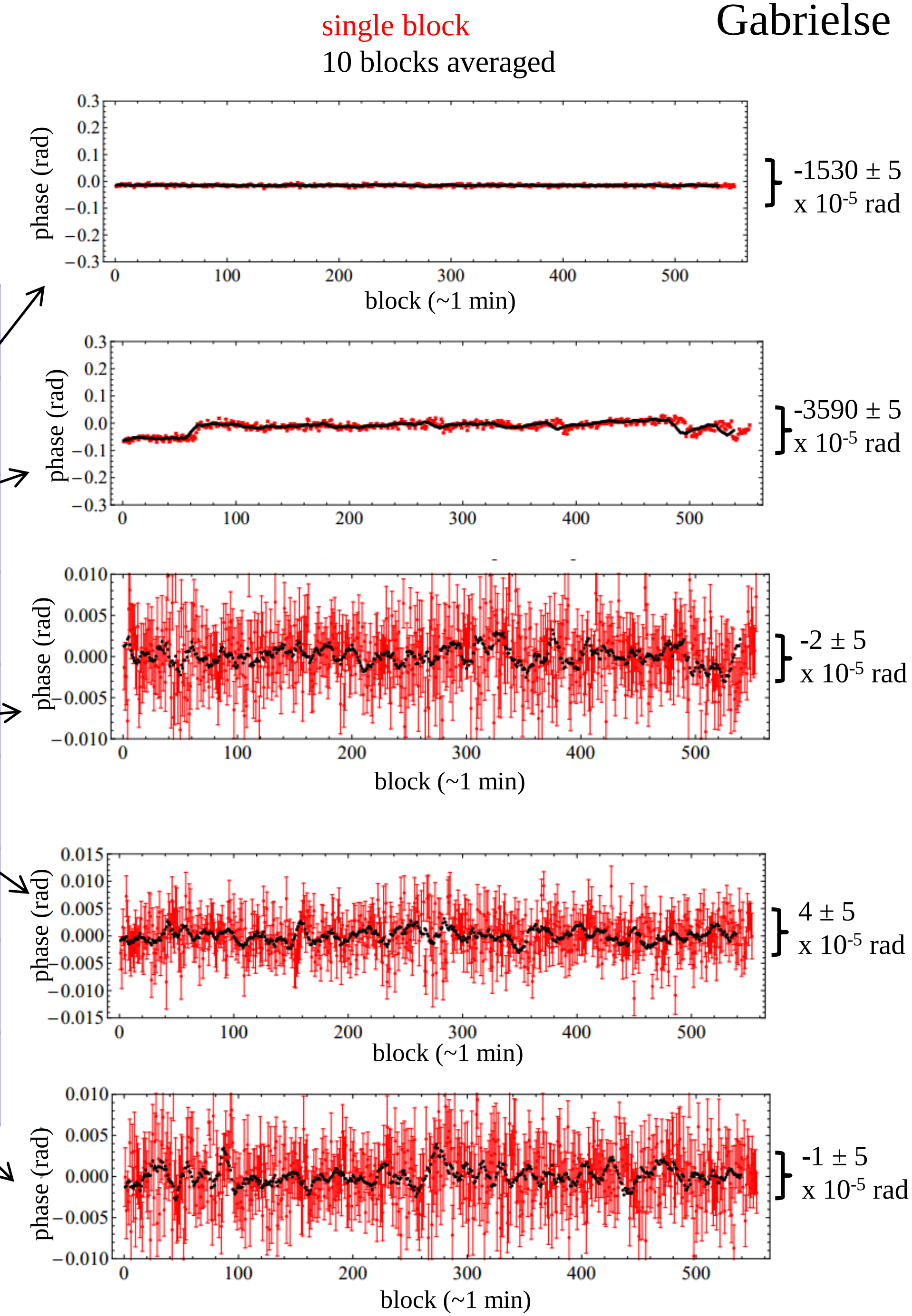
392 ± 5 x 10^{-5} rad



??? ± 5 x 10^{-5} rad

Gabrielse

Parity sum (*N*•*E*•*B*)	**Derived quantities**
+ + +	$B_{nr}\ g\ \mu\ \tau + \theta_{nr}$
+ + -	$B_0\, g\ \mu\ \tau$
+ - +	$B_{leak}\, g\ \mu\ \tau$
+ - -	0
- + +	$B_{nr}\ \Delta g\ \mu\ \tau$
- + -	$B_0\ \Delta g\ \mu\ \tau$
- - +	$d_e\ E_{eff}\ \ \tau$
- - -	$B_0\ \ \eta\ E_{nr}\ \mu\ \tau$



-1530 ± 5 x 10^{-5} rad

-3590 ± 5 x 10^{-5} rad

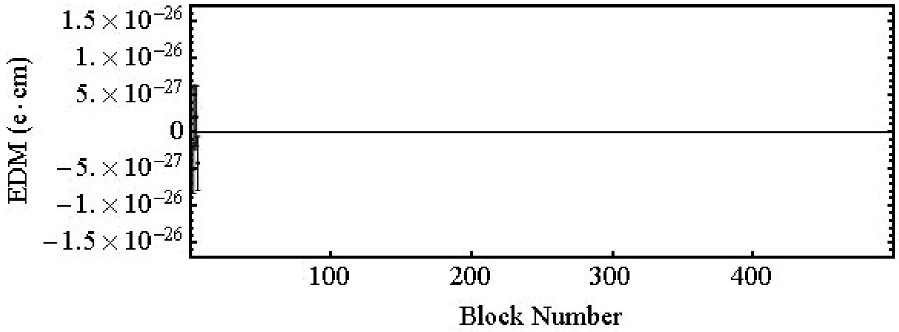
-2 ± 5 x 10^{-5} rad

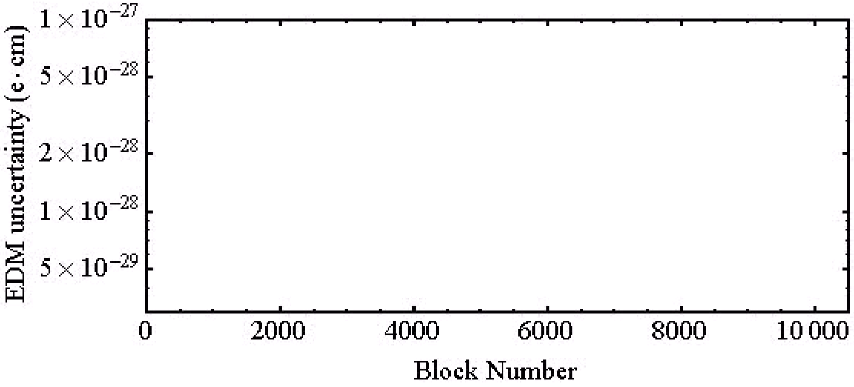
4 ± 5 x 10^{-5} rad

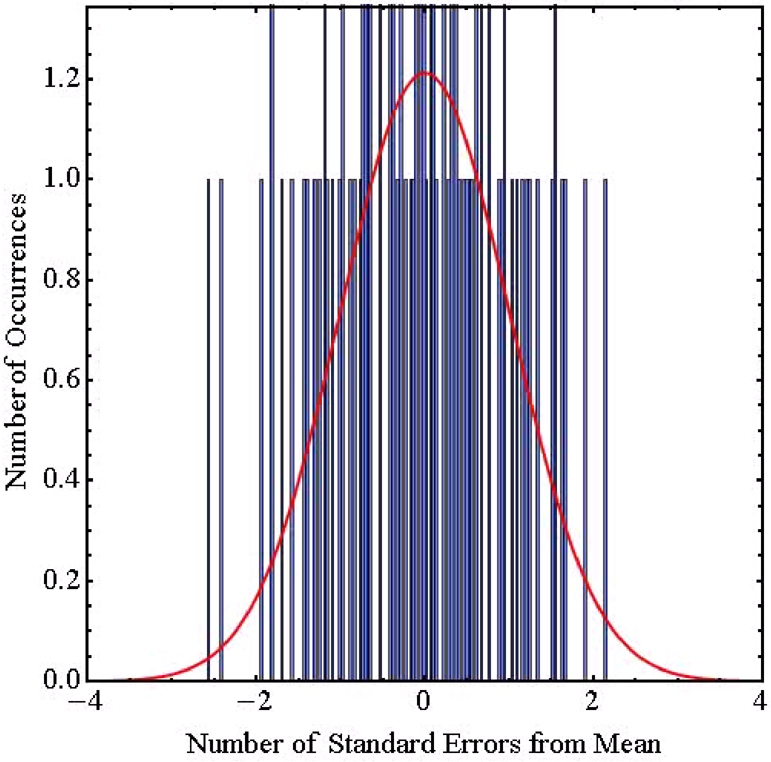
-1 ± 5 x 10^{-5} rad

EDM Measurements – 2013 data

- 10,000 blocks of data → 200,000 independent EDM measurements
- ~2 weeks of integration time

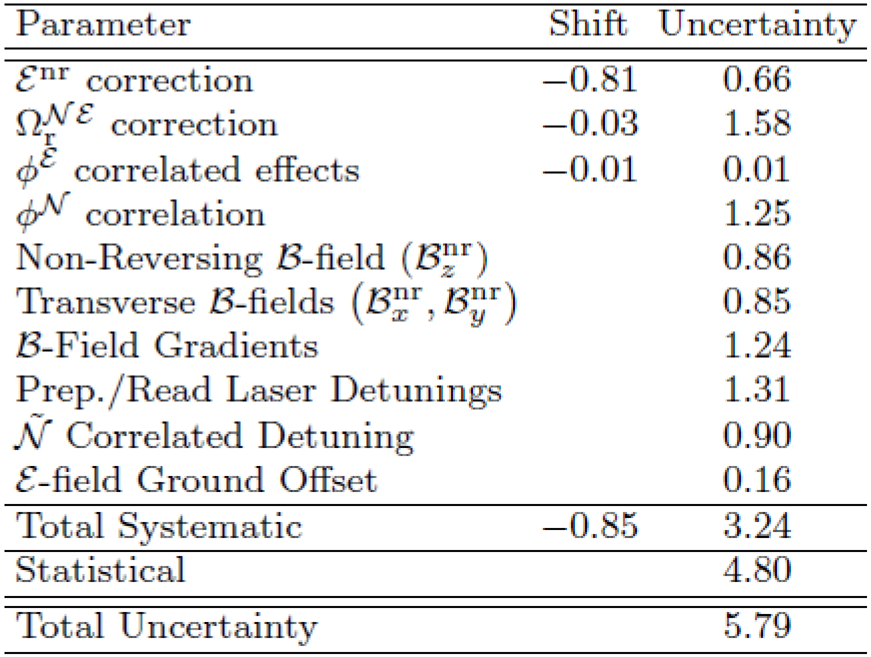






Uncertainties

- ~ 40 systematics checks
- Where possible we exaggerated the effect (e.g B gradients)

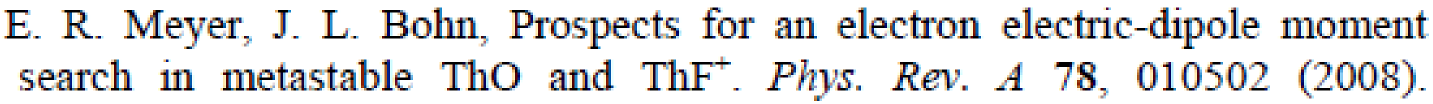


Parameter	Shift	Uncertainty
$\mathcal{E}^{\mathrm{nr}}$ correction	-0.81	0.66
$\Omega_{\mathrm{r}}^{\mathcal{N}\mathcal{E}}$ correction	-0.03	1.58
$\phi^{\mathcal{E}}$ correlated effects	-0.01	0.01
$\phi^{\mathcal{N}}$ correlation		1.25
Non-Reversing $\mathcal{B}$-field $(\mathcal{B}_z^{\mathrm{nr}})$		0.86
Transverse $\mathcal{B}$-fields $(\mathcal{B}_x^{\mathrm{nr}}, \mathcal{B}_y^{\mathrm{nr}})$		0.85
$\mathcal{B}$-Field Gradients		1.24
Prep./Read Laser Detunings		1.31
$\tilde{\mathcal{N}}$ Correlated Detuning		0.90
$\mathcal{E}$-field Ground Offset		0.16
Total Systematic	-0.85	3.24
Statistical		4.80
Total Uncertainty		5.79

TABLE I. Systematic and statistical errors for $\omega^{\mathcal{N}\mathcal{E}}$, in units of mrad/s. All errors are added in quadrature. In EDM units, 1.3 mrad/s $\approx 10^{-29}$ e cm.

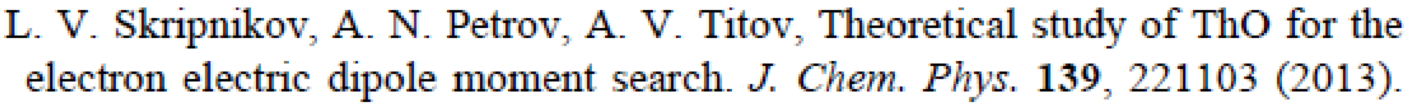
Need Effective Electric Field (from Theory) to Extract EDM

104 GV/cm



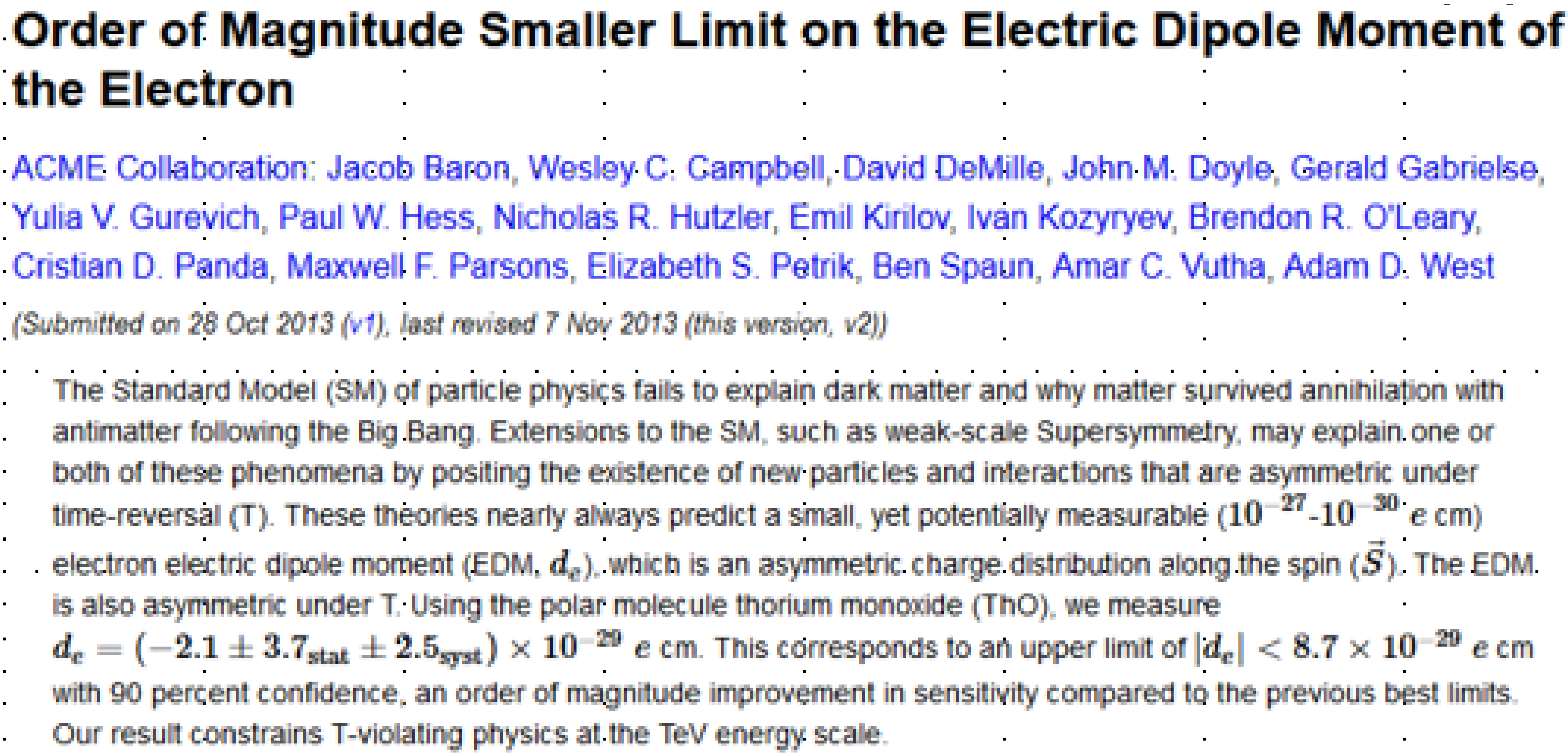
E. R. Meyer, J. L. Bohn, Prospects for an electron electric-dipole moment search in metastable ThO and ThF^+. *Phys. Rev. A* **78**, 010502 (2008).

84 GV/cm



L. V. Skripnikov, A. N. Petrov, A. V. Titov, Theoretical study of ThO for the electron electric dipole moment search. *J. Chem. Phys.* **139**, 221103 (2013).

75.6 GV/cm (3 %) ← preprint arrived from India this morning
T. Flieg and M.K. Nayak
relativistic, configuration interaction



Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

ACME Collaboration: Jacob Baron, Wesley C. Campbell, David DeMille, John M. Doyle, Gerald Gabrielse, Yulia V. Gurevich, Paul W. Hess, Nicholas R. Hutzler, Emil Kirilov, Ivan Kozyryev, Brendon R. O'Leary, Cristian D. Panda, Maxwell F. Parsons, Elizabeth S. Petrik, Ben Spaun, Amar C. Vutha, Adam D. West

(Submitted on 28 Oct 2013 (v1), last revised 7 Nov 2013 (this version, v2))

The Standard Model (SM) of particle physics fails to explain dark matter and why matter survived annihilation with antimatter following the Big Bang. Extensions to the SM, such as weak-scale Supersymmetry, may explain one or both of these phenomena by positing the existence of new particles and interactions that are asymmetric under time-reversal (T). These theories nearly always predict a small, yet potentially measurable (10^{-27}-10^{-30} e cm) electron electric dipole moment (EDM, d_e), which is an asymmetric charge distribution along the spin ($\vec{S}$). The EDM is also asymmetric under T. Using the polar molecule thorium monoxide (ThO), we measure $d_e = (-2.1 \pm 3.7_{\rm stat} \pm 2.5_{\rm syst}) \times 10^{-29}$ e cm. This corresponds to an upper limit of $|d_e| < 8.7 \times 10^{-29}$ e cm with 90 percent confidence, an order of magnitude improvement in sensitivity compared to the previous best limits. Our result constrains T-violating physics at the TeV energy scale.

$$d_e = (-2.1 \pm 3.7_{\rm stat} \pm 2.5_{\rm syst}) \times 10^{-29}\ e\ \text{cm}.$$

$$\boxed{|d_e| < 8.7 \times 10^{-29}\ e\ \text{cm}}$$

We actually constrain the EDM and C_S

$$-d_e\mathcal{E}_{\text{eff}} - W_S C_S$$

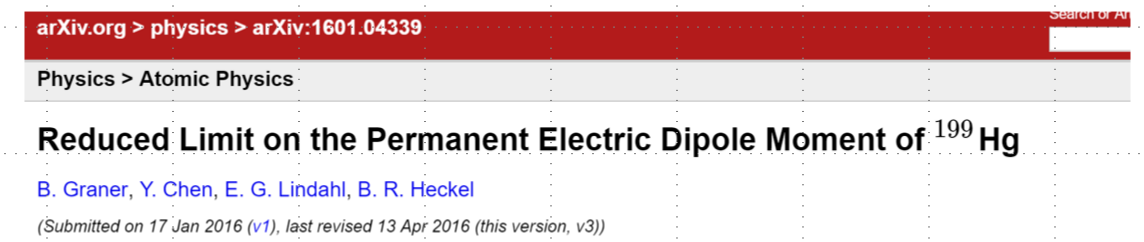
$$C_S = (-1.3 \pm 3.0) \times 10^{-9}$$

$$\boxed{|C_S| < 5.9 \times 10^{-9}}$$

Assuming d=0

From molecular calculation

Sensitivity to Other CP Violating Observables illustrated in Recent Hg EDM Measurement



arXiv.org > physics > arXiv:1601.04339

Search or Ar

Physics > Atomic Physics

Reduced Limit on the Permanent Electric Dipole Moment of ^{199}Hg

B. Graner, Y. Chen, E. G. Lindahl, B. R. Heckel

(Submitted on 17 Jan 2016 (v1), last revised 13 Apr 2016 (this version, v3))

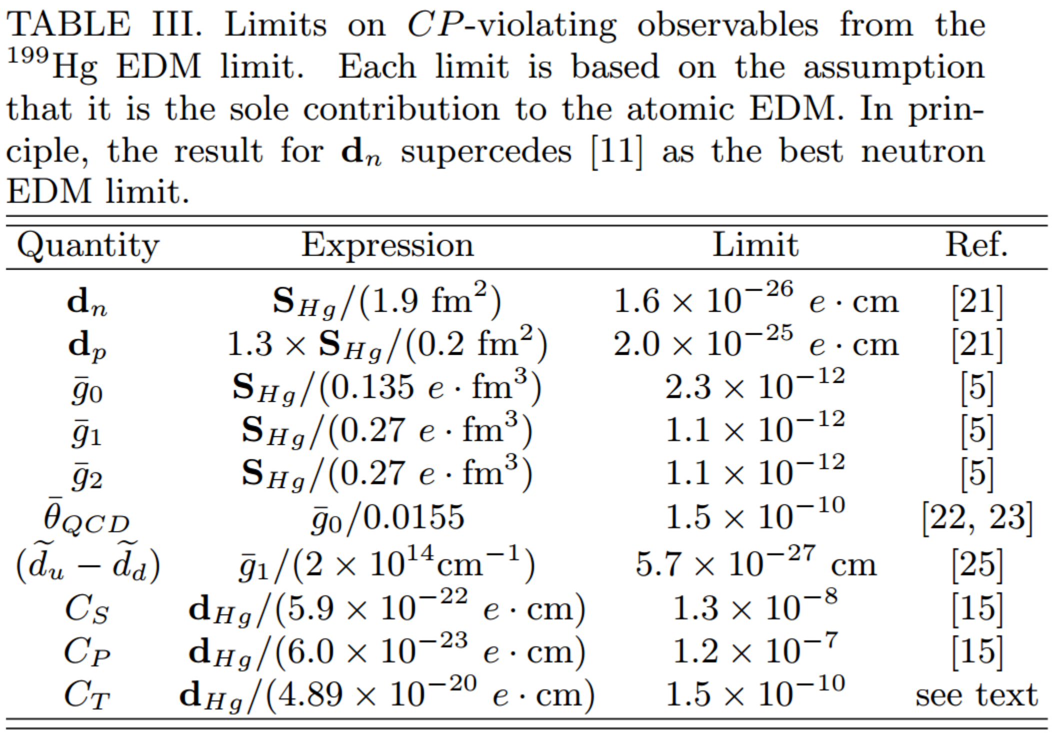


TABLE III. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{Hg}/(1.9\ \mathrm{fm}^2)$	$1.6 \times 10^{-26}\ e \cdot \mathrm{cm}$	[21]
$\mathbf{d}_p$	$1.3 \times \mathbf{S}_{Hg}/(0.2\ \mathrm{fm}^2)$	$2.0 \times 10^{-25}\ e \cdot \mathrm{cm}$	[21]
$\bar{g}_0$	$\mathbf{S}_{Hg}/(0.135\ e \cdot \mathrm{fm}^3)$	2.3×10^{-12}	[5]
$\bar{g}_1$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{g}_2$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{\theta}_{QCD}$	$\bar{g}_0/0.0155$	1.5×10^{-10}	[22, 23]
$(\widetilde{d}_u - \widetilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14}\mathrm{cm}^{-1})$	$5.7 \times 10^{-27}\ \mathrm{cm}$	[25]
C_S	$\mathbf{d}_{Hg}/(5.9 \times 10^{-22}\ e \cdot \mathrm{cm})$	1.3×10^{-8}	[15]
C_P	$\mathbf{d}_{Hg}/(6.0 \times 10^{-23}\ e \cdot \mathrm{cm})$	1.2×10^{-7}	[15]
C_T	$\mathbf{d}_{Hg}/(4.89 \times 10^{-20}\ e \cdot \mathrm{cm})$	1.5×10^{-10}	see text

Constraining New Physics on the 1 to 3 TeV Scale

for weak interactions
~4/137

difficult to suppress
new CP violating phase

$\sin(\phi_{CP}) \sim 1$

$$\frac{d_e}{e} \sim \kappa \left(\frac{\alpha_{\text{eff}}}{4\pi}\right)^n \left(\frac{m_e c^2}{\Lambda^2}\right) \sin(\phi_{CP}) (\hbar c)$$

mass scale of
new particles

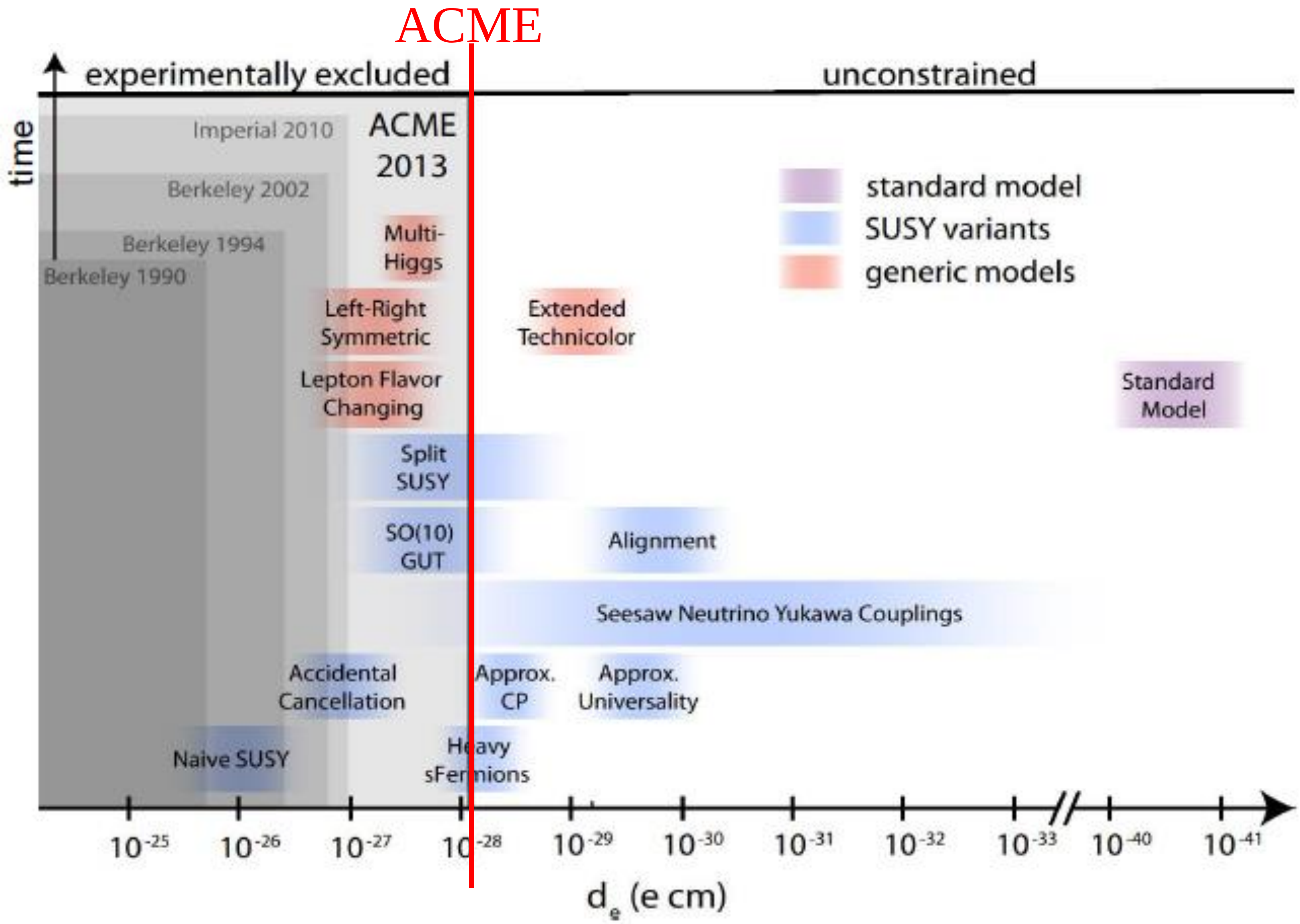
prefactor
$\kappa \sim 0.1$ to 1

conservative

couples to weak interaction via
n=1 or n=2 loop diagrams
3 TeV   1 TeV

Probing same mass scale as the LHC

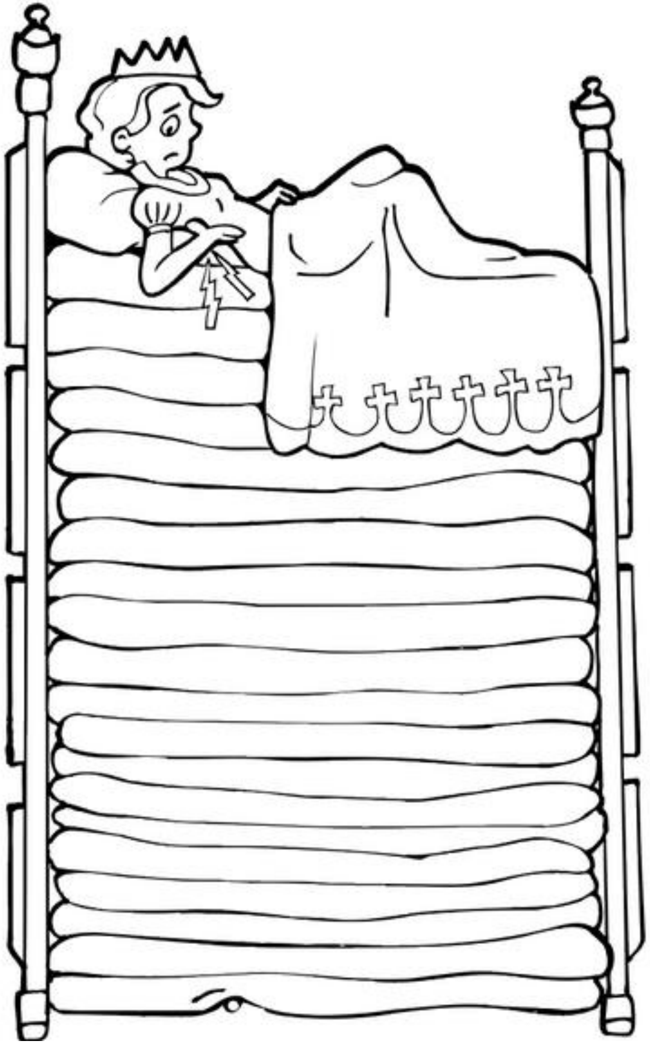
2014 ACME Electron EDM Measurement



W. Bernreuther, M. Suzuki, *Rev. Mod. Phys.* **63**, 313 (1991)

How Big is 8×10^{-29} e cm?

How sensitive was our princess to the hidden pea?



Scale size of the polarization cloud around the electron → earth

Shift in earth center by 2 nm

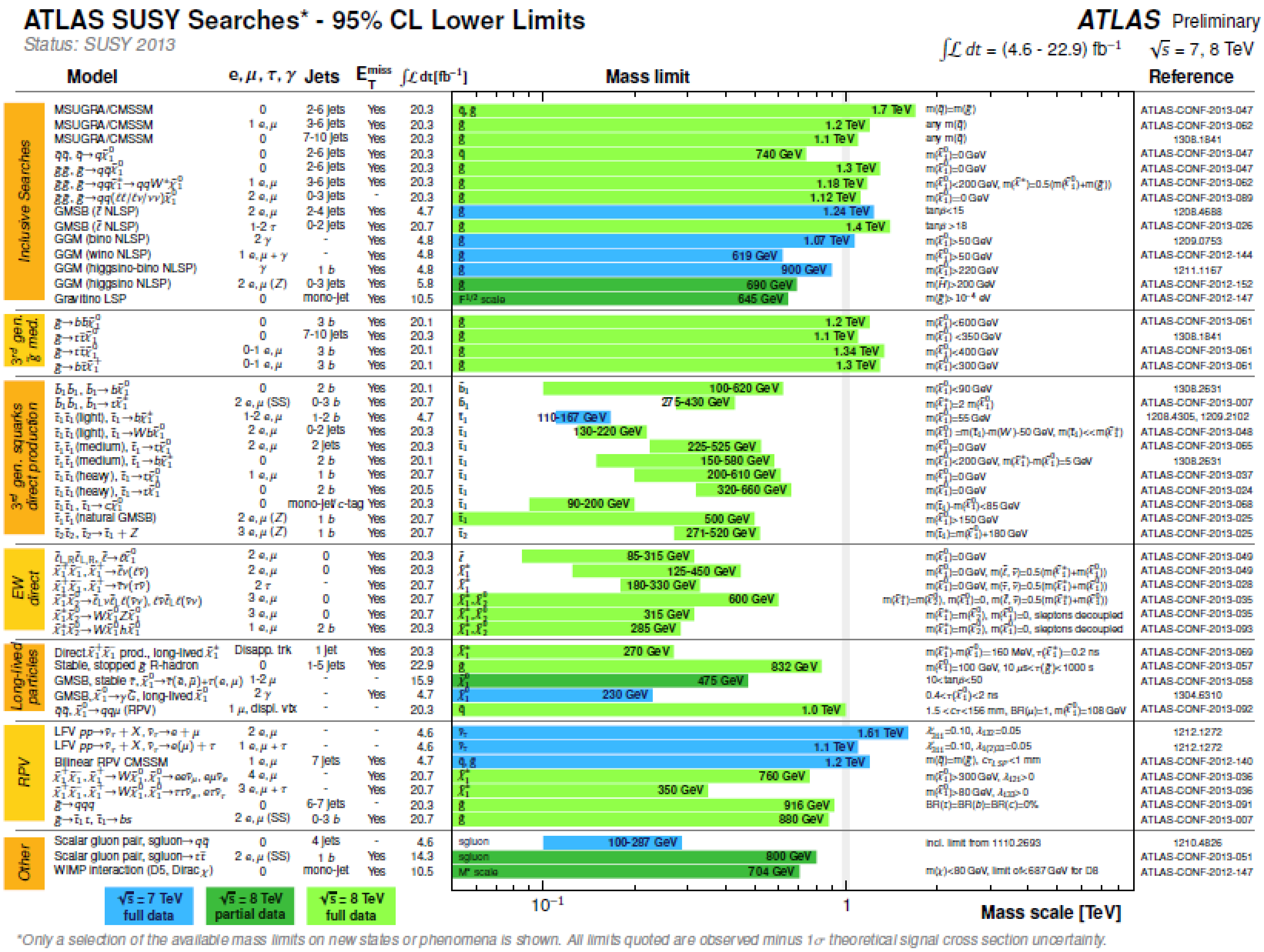
earth-sized polarization cloud around electron (scale classical electron radius)

Relationship to LHC Physics

The LHC is exciting and important but EDMs also play a role

- should get an improved electron EDM on the LHC time scale
- If the LHC sees new particles, is CP violation involved?
- If the LHC sees nothing, EDM game is the only one in town

- Would be great to use LHC results and ours together to see what we have learned together about Standard Model extensions



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

$\int\mathcal{L}\,dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7,\ 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde q, \tilde g$ 1.7 TeV	$m(\tilde q)=m(\tilde g)$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde g$ 1.2 TeV	any $m(\tilde q)$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde g$ 1.1 TeV	any $m(\tilde q)$	1308.1841
	$\tilde q\tilde q$, $\tilde q\to q\tilde\chi_1^0$	0	2-6 jets	Yes	20.3	$\tilde q$ 740 GeV	$m(\tilde\chi_1^0)=0$ GeV	ATLAS-CONF-2013-047
	$\tilde g\tilde g$, $\tilde g\to q\bar q\tilde\chi_1^0$	0	2-6 jets	Yes	20.3	$\tilde g$ 1.3 TeV	$m(\tilde\chi_1^0)=0$ GeV	ATLAS-CONF-2013-047
	$\tilde g\tilde g$, $\tilde g\to qq\tilde\chi_1^\pm\to qqW^\pm\tilde\chi_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde g$ 1.18 TeV	$m(\tilde\chi_1^0)<200$ GeV, $m(\tilde\chi^\pm)=0.5(m(\tilde\chi_1^0)+m(\tilde g))$	ATLAS-CONF-2013-062
	$\tilde g\tilde g$, $\tilde g\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde\chi_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde g$ 1.12 TeV	$m(\tilde\chi_1^0)=0$ GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde\ell$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde g$ 1.24 TeV	$\tan\beta<15$	1208.4688
	GMSB ($\tilde\tau$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde g$ 1.4 TeV	$\tan\beta>18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde g$ 1.07 TeV	$m(\tilde\chi_1^0)>50$ GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde g$ 619 GeV	$m(\tilde\chi_1^0)>50$ GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde g$ 900 GeV	$m(\tilde\chi_1^0)>220$ GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde g$ 690 GeV	$m(\tilde H)>200$ GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde G)>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde g$ med.	$\tilde g\to b\bar b\tilde\chi_1^0$	0	3 b	Yes	20.1	$\tilde g$ 1.2 TeV	$m(\tilde\chi_1^0)<600$ GeV	ATLAS-CONF-2013-061
	$\tilde g\to t\bar t\tilde\chi_1^0$	0	7-10 jets	Yes	20.3	$\tilde g$ 1.1 TeV	$m(\tilde\chi_1^0)<350$ GeV	1308.1841
	$\tilde g\to t\bar t\tilde\chi_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$ 1.34 TeV	$m(\tilde\chi_1^0)<400$ GeV	ATLAS-CONF-2013-061
	$\tilde g\to b\bar t\tilde\chi_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde g$ 1.3 TeV	$m(\tilde\chi_1^0)<300$ GeV	ATLAS-CONF-2013-061
3rd gen. squarks direct production	$\tilde b_1\tilde b_1$, $\tilde b_1\to b\tilde\chi_1^0$	0	2 b	Yes	20.1	$\tilde b_1$ 100-620 GeV	$m(\tilde\chi_1^0)<90$ GeV	1308.2631
	$\tilde b_1\tilde b_1$, $\tilde b_1\to t\tilde\chi_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde b_1$ 275-430 GeV	$m(\tilde\chi_1^\pm)=2\,m(\tilde\chi_1^0)$	ATLAS-CONF-2013-007
	$\tilde t_1\tilde t_1$ (light), $\tilde t_1\to b\tilde\chi_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde t_1$ 110-167 GeV	$m(\tilde\chi_1^0)=55$ GeV	1208.4305, 1209.2102
	$\tilde t_1\tilde t_1$ (light), $\tilde t_1\to Wb\tilde\chi_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde t_1$ 130-220 GeV	$m(\tilde\chi_1^0)=m(\tilde t_1)-m(W)-50$ GeV, $m(\tilde t_1)<<m(\tilde\chi_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde t_1\tilde t_1$ (medium), $\tilde t_1\to t\tilde\chi_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde t_1$ 225-525 GeV	$m(\tilde\chi_1^0)=0$ GeV	ATLAS-CONF-2013-065
	$\tilde t_1\tilde t_1$ (medium), $\tilde t_1\to b\tilde\chi_1^\pm$	0	2 b	Yes	20.1	$\tilde t_1$ 150-580 GeV	$m(\tilde\chi_1^0)<200$ GeV, $m(\tilde\chi_1^\pm)-m(\tilde\chi_1^0)=5$ GeV	1308.2631
	$\tilde t_1\tilde t_1$ (heavy), $\tilde t_1\to t\tilde\chi_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde t_1$ 200-610 GeV	$m(\tilde\chi_1^0)=0$ GeV	ATLAS-CONF-2013-037
	$\tilde t_1\tilde t_1$ (heavy), $\tilde t_1\to t\tilde\chi_1^0$	0	2 b	Yes	20.5	$\tilde t_1$ 320-660 GeV	$m(\tilde\chi_1^0)=0$ GeV	ATLAS-CONF-2013-024
	$\tilde t_1\tilde t_1$, $\tilde t_1\to c\tilde\chi_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde t_1$ 90-200 GeV	$m(\tilde t_1)-m(\tilde\chi_1^0)<85$ GeV	ATLAS-CONF-2013-068
	$\tilde t_1\tilde t_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde t_1$ 500 GeV	$m(\tilde\chi_1^0)>150$ GeV	ATLAS-CONF-2013-025
	$\tilde t_2\tilde t_2$, $\tilde t_2\to\tilde t_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde t_2$ 271-520 GeV	$m(\tilde t_1)=m(\tilde\chi_1^0)+180$ GeV	ATLAS-CONF-2013-025
EW direct	$\tilde\ell_{L,R}\tilde\ell_{L,R}$, $\tilde\ell\to\ell\tilde\chi_1^0$	2 e,μ	0	Yes	20.3	$\tilde\ell$ 85-315 GeV	$m(\tilde\chi_1^0)=0$ GeV	ATLAS-CONF-2013-049
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to\tilde\ell\nu(\ell\tilde\nu)$	2 e,μ	0	Yes	20.3	$\tilde\chi_1^\pm$ 125-450 GeV	$m(\tilde\chi_1^0)=0$ GeV, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	ATLAS-CONF-2013-049
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to\tilde\tau\nu(\tau\tilde\nu)$	2 τ	-	Yes	20.7	$\tilde\chi_1^\pm$ 180-330 GeV	$m(\tilde\chi_1^0)=0$ GeV, $m(\tilde\tau,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	ATLAS-CONF-2013-028
	$\tilde\chi_1^\pm\tilde\chi_2^0\to\tilde\ell_L\nu\tilde\ell_L\ell(\tilde\nu\nu)$, $\ell\tilde\nu\tilde\ell_L\ell(\tilde\nu\nu)$	3 e,μ	0	Yes	20.7	$\tilde\chi_1^\pm$, $\tilde\chi_2^0$ 600 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)=0$, $m(\tilde\ell,\tilde\nu)=0.5(m(\tilde\chi_1^\pm)+m(\tilde\chi_1^0))$	ATLAS-CONF-2013-035
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0Z\tilde\chi_1^0$	3 e,μ	0	Yes	20.7	$\tilde\chi_1^\pm$, $\tilde\chi_2^0$ 315 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)=0$, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde\chi_1^\pm\tilde\chi_2^0\to W\tilde\chi_1^0h\tilde\chi_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde\chi_1^\pm$, $\tilde\chi_2^0$ 285 GeV	$m(\tilde\chi_1^\pm)=m(\tilde\chi_2^0)$, $m(\tilde\chi_1^0)=0$, sleptons decoupled	ATLAS-CONF-2013-093
Long-lived particles	Direct $\tilde\chi_1^+\tilde\chi_1^-$ prod., long-lived $\tilde\chi_1^\pm$	Disapp. trk	1 jet	Yes	20.3	$\tilde\chi_1^\pm$ 270 GeV	$m(\tilde\chi_1^\pm)-m(\tilde\chi_1^0)=160$ MeV, $\tau(\tilde\chi_1^\pm)=0.2$ ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde g$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde g$ 832 GeV	$m(\tilde\chi_1^0)=100$ GeV, 10 μs $<\tau(\tilde g)<$ 1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde\tau$, $\tilde\chi_1^0\to\tilde\tau(\tilde e,\tilde\mu)+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde\chi_1^0$ 475 GeV	$10<\tan\beta<50$	ATLAS-CONF-2013-058
	GMSB, $\tilde\chi_1^0\to\gamma\tilde G$, long-lived $\tilde\chi_1^0$	2 γ	-	Yes	4.7	$\tilde\chi_1^0$ 230 GeV	$0.4<\tau(\tilde\chi_1^0)<2$ ns	1304.6310
	$\tilde q\tilde q$, $\tilde\chi_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde q$ 1.0 TeV	$1.5<c\tau<156$ mm, BR(μ)=1, $m(\tilde\chi_1^0)=108$ GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde\nu_\tau$ 1.61 TeV	$\lambda'_{311}=0.10$, $\lambda_{132}=0.05$	1212.1272
	LFV $pp\to\tilde\nu_\tau+X$, $\tilde\nu_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde\nu_\tau$ 1.1 TeV	$\lambda'_{311}=0.10$, $\lambda_{1(2)33}=0.05$	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde q,\tilde g$ 1.2 TeV	$m(\tilde q)=m(\tilde g)$, $c\tau_{LSP}<1$ mm	ATLAS-CONF-2012-140
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to W\tilde\chi_1^0$, $\tilde\chi_1^0\to ee\tilde\nu_\mu$, $e\mu\tilde\nu_e$	4 e,μ	-	Yes	20.7	$\tilde\chi_1^\pm$ 760 GeV	$m(\tilde\chi_1^0)>300$ GeV, $\lambda_{121}>0$	ATLAS-CONF-2013-036
	$\tilde\chi_1^+\tilde\chi_1^-$, $\tilde\chi_1^+\to W\tilde\chi_1^0$, $\tilde\chi_1^0\to\tau\tau\tilde\nu_e$, $e\tau\tilde\nu_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde\chi_1^\pm$ 350 GeV	$m(\tilde\chi_1^0)>80$ GeV, $\lambda_{133}>0$	ATLAS-CONF-2013-036
	$\tilde g\to qqq$	0	6-7 jets	-	20.3	$\tilde g$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde g\to\tilde t_1t$, $\tilde t_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde g$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar q$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar t$	2 e,μ (SS)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)<80$ GeV, limit of <687 GeV for D8	ATLAS-CONF-2012-147

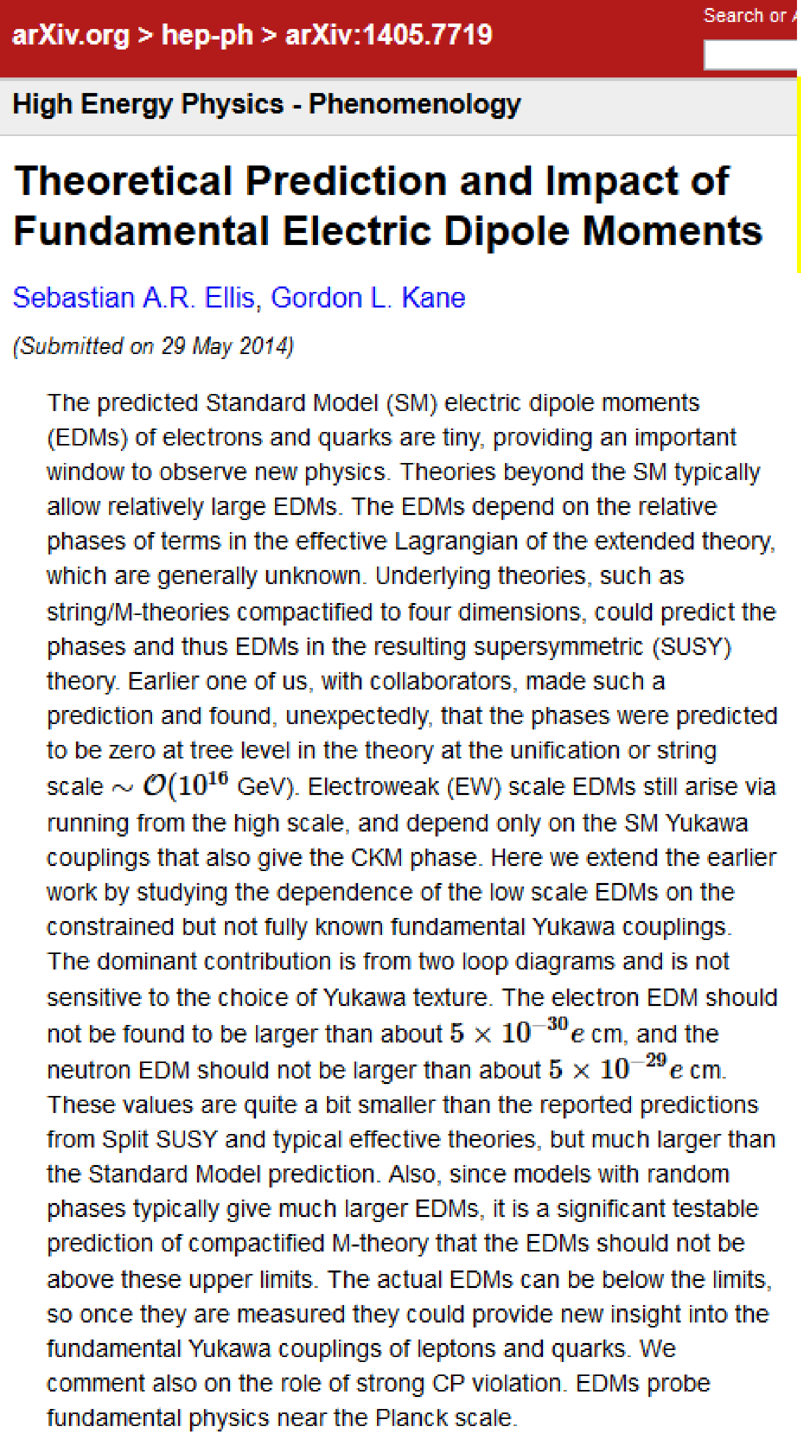
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

https://twiki.cern.ch/twiki/pub/AtlasPublic/CombinedSummaryPlots/AtlasSearchesSUSY_SUSY2013.pdf

Lots of Theory Papers in Reaction to the ACME Limit

~ 40 papers in a couple months

EDM should be just smaller than our limit



High Energy Physics - Phenomenology

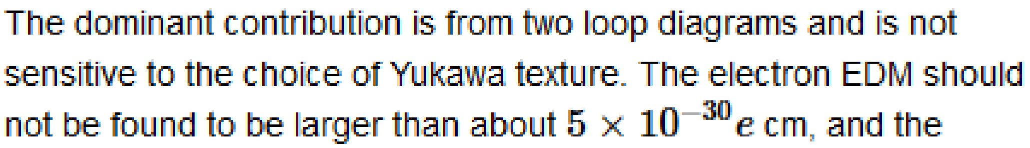
Theoretical Prediction and Impact of Fundamental Electric Dipole Moments

Sebastian A.R. Ellis, Gordon L. Kane

(Submitted on 29 May 2014)

The predicted Standard Model (SM) electric dipole moments (EDMs) of electrons and quarks are tiny, providing an important window to observe new physics. Theories beyond the SM typically allow relatively large EDMs. The EDMs depend on the relative phases of terms in the effective Lagrangian of the extended theory, which are generally unknown. Underlying theories, such as string/M-theories compactified to four dimensions, could predict the phases and thus EDMs in the resulting supersymmetric (SUSY) theory. Earlier one of us, with collaborators, made such a prediction and found, unexpectedly, that the phases were predicted to be zero at tree level in the theory at the unification or string scale $\sim \mathcal{O}(10^{16}$ GeV). Electroweak (EW) scale EDMs still arise via running from the high scale, and depend only on the SM Yukawa couplings that also give the CKM phase. Here we extend the earlier work by studying the dependence of the low scale EDMs on the constrained but not fully known fundamental Yukawa couplings. The dominant contribution is from two loop diagrams and is not sensitive to the choice of Yukawa texture. The electron EDM should not be found to be larger than about $5 \times 10^{-30} e$ cm, and the neutron EDM should not be larger than about $5 \times 10^{-29} e$ cm. These values are quite a bit smaller than the reported predictions from Split SUSY and typical effective theories, but much larger than the Standard Model prediction. Also, since models with random phases typically give much larger EDMs, it is a significant testable prediction of compactified M-theory that the EDMs should not be above these upper limits. The actual EDMs can be below the limits, so once they are measured they could provide new insight into the fundamental Yukawa couplings of leptons and quarks. We comment also on the role of strong CP violation. EDMs probe fundamental physics near the Planck scale.

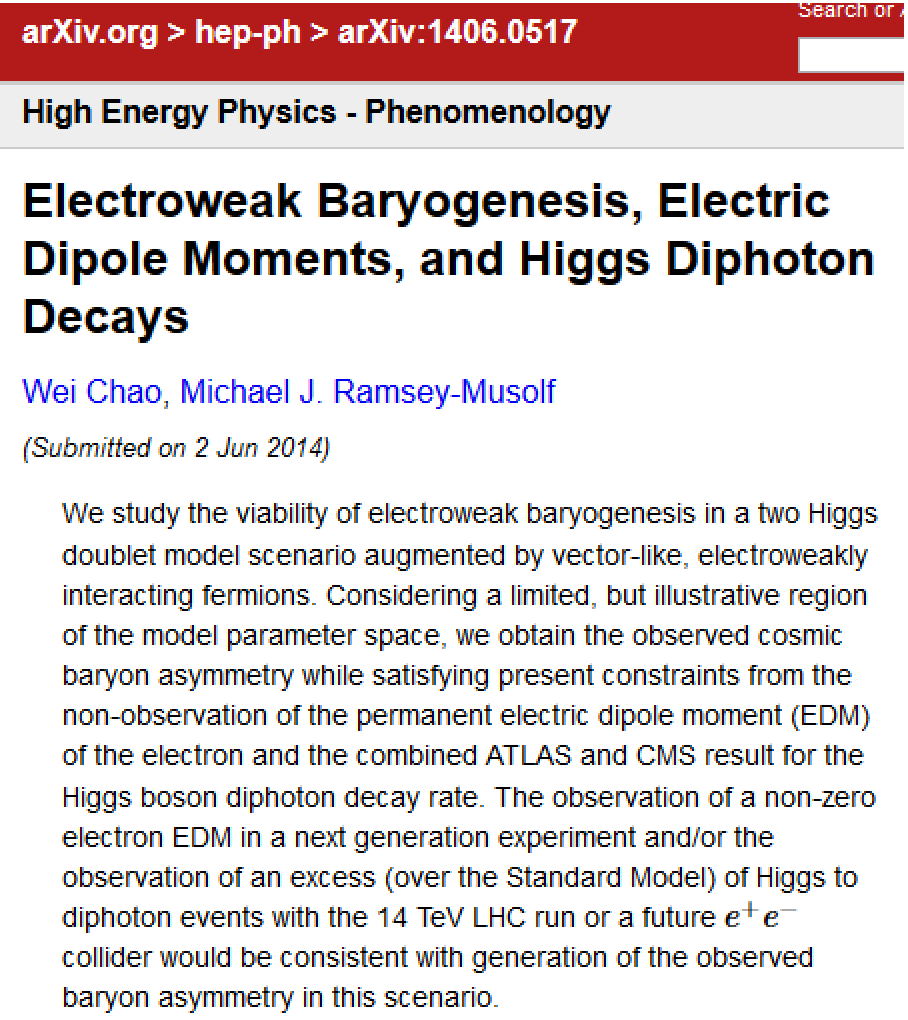
"Testable prediction of compatified M-theory"



The dominant contribution is from two loop diagrams and is not sensitive to the choice of Yukawa texture. The electron EDM should not be found to be larger than about $5 \times 10^{-30} e$ cm, and the

should not be … larger than

One Baryogenesis Model



Search or

arXiv.org > hep-ph > arXiv:1406.0517

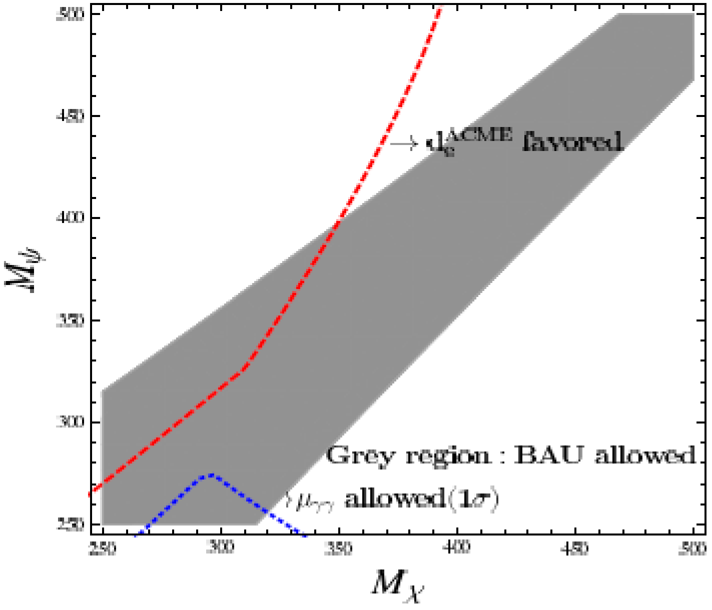
High Energy Physics - Phenomenology

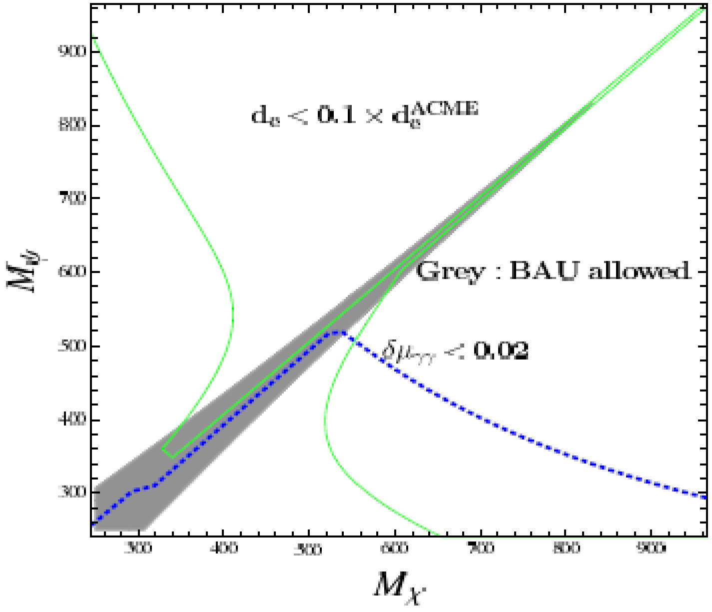
Electroweak Baryogenesis, Electric Dipole Moments, and Higgs Diphoton Decays

Wei Chao, Michael J. Ramsey-Musolf

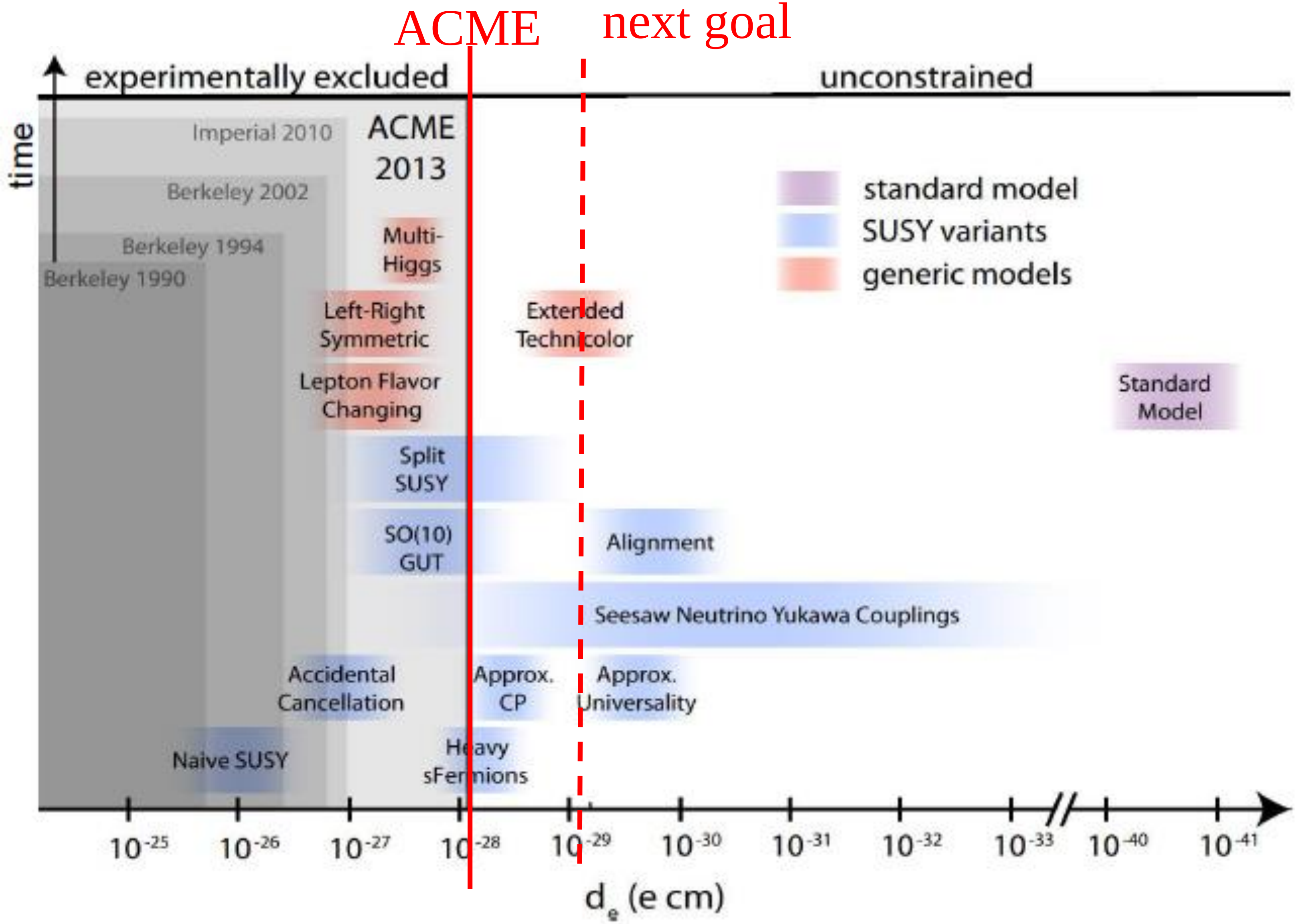
(Submitted on 2 Jun 2014)

We study the viability of electroweak baryogenesis in a two Higgs doublet model scenario augmented by vector-like, electroweakly interacting fermions. Considering a limited, but illustrative region of the model parameter space, we obtain the observed cosmic baryon asymmetry while satisfying present constraints from the non-observation of the permanent electric dipole moment (EDM) of the electron and the combined ATLAS and CMS result for the Higgs boson diphoton decay rate. The observation of a non-zero electron EDM in a next generation experiment and/or the observation of an excess (over the Standard Model) of Higgs to diphoton events with the 14 TeV LHC run or a future e^+e^- collider would be consistent with generation of the observed baryon asymmetry in this scenario.





ACME → Nearing Data Taking for Generation II



W. Bernreuther, M. Suzuki, *Rev. Mod. Phys.* **63**, 313 (1991)

STIRAP, etc. Improvements

PHYSICAL REVIEW A **93**, 052110 (2016)

Stimulated Raman adiabatic passage preparation of a coherent superposition of ThO $H\,^3\Delta_1$ states for an improved electron electric-dipole-moment measurement

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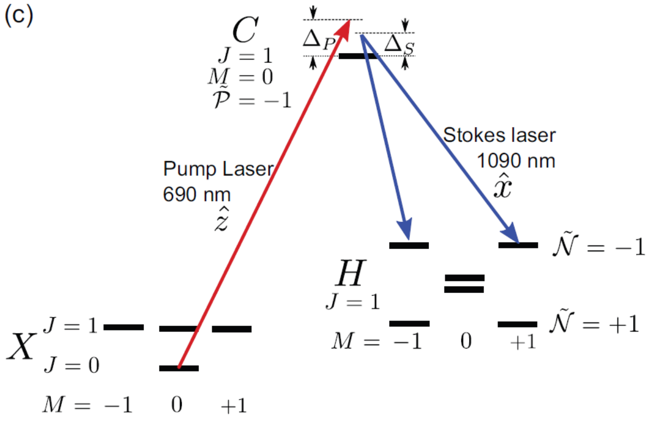
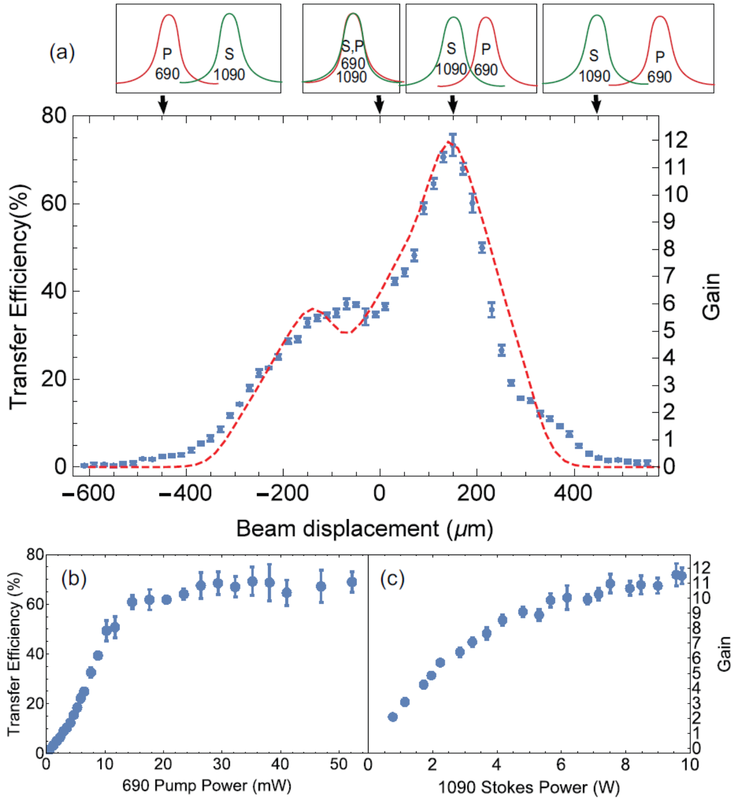
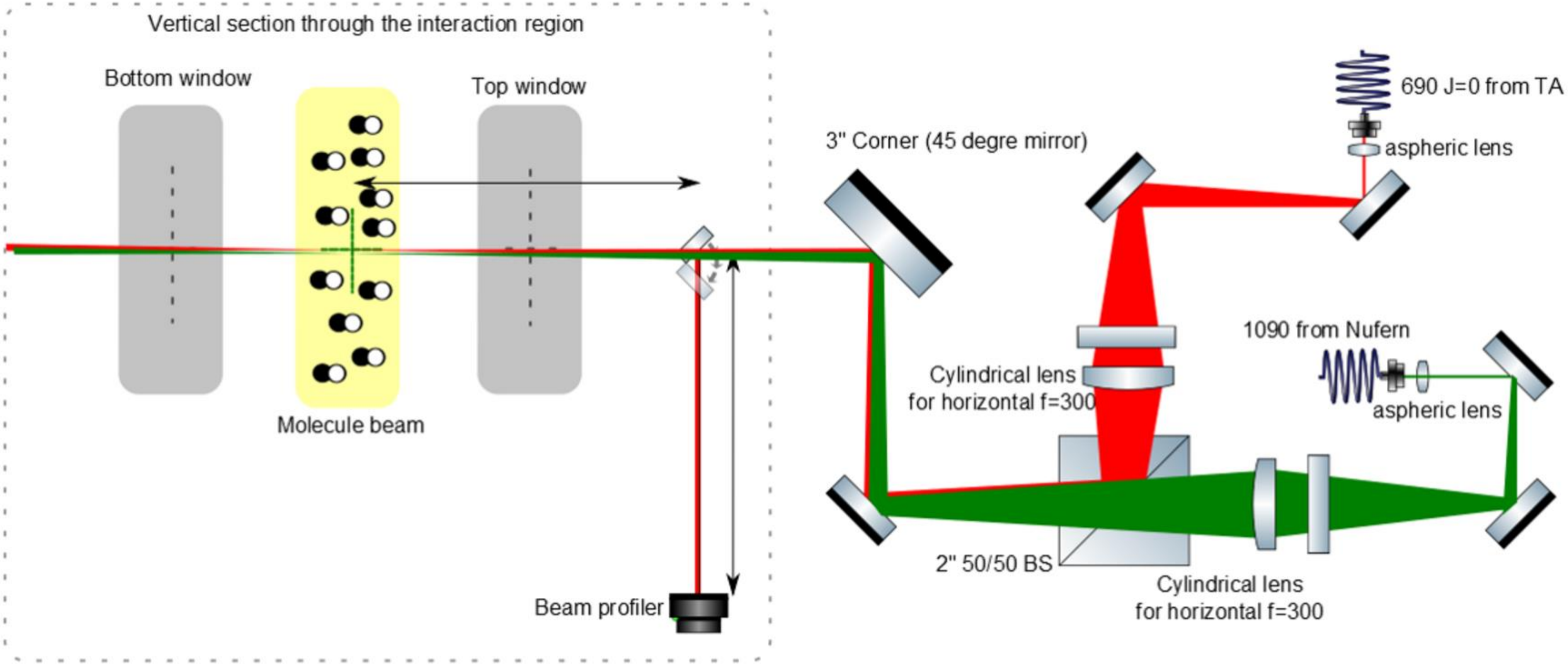
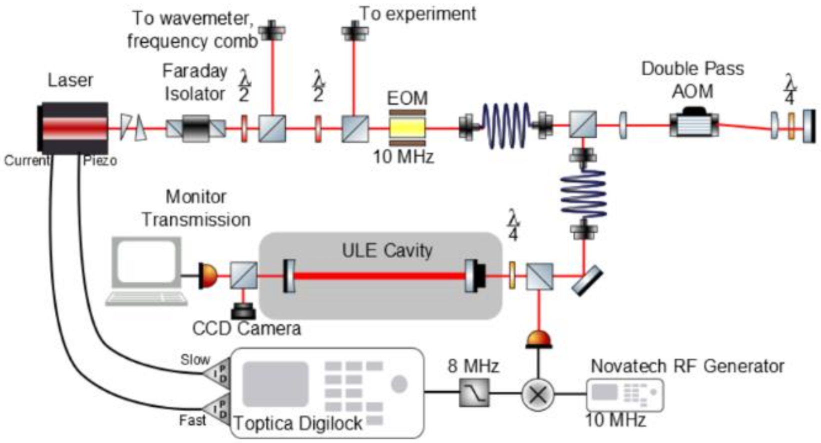
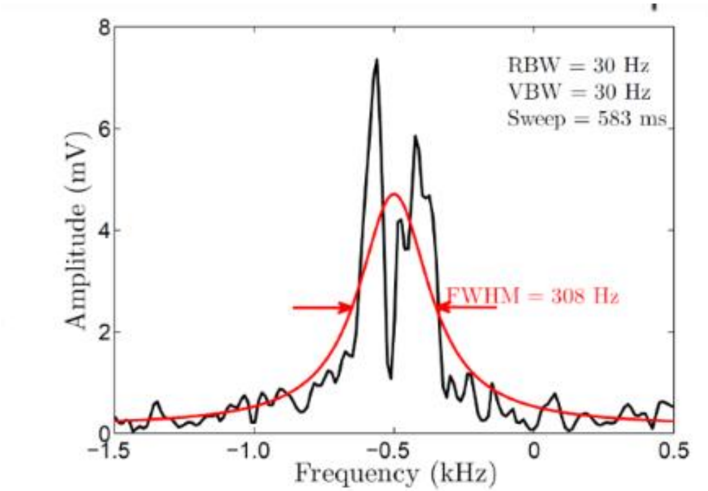


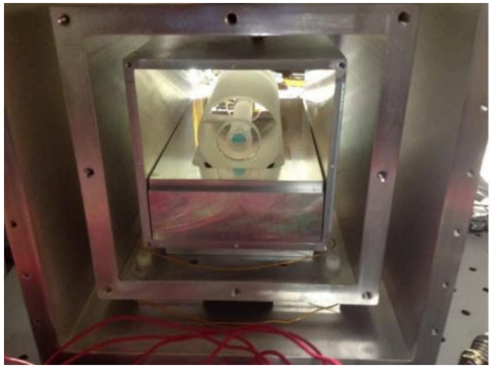


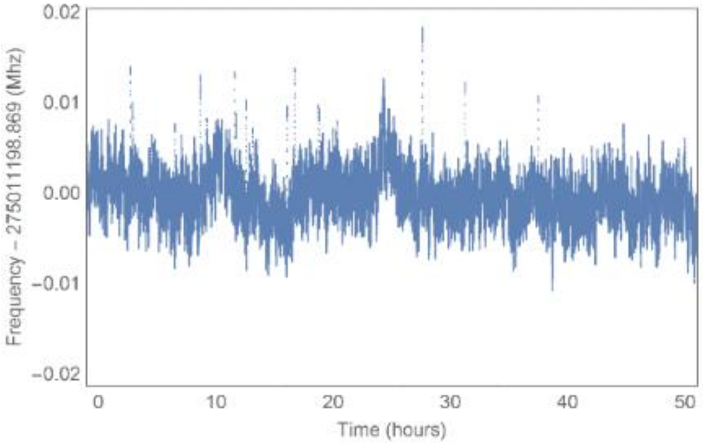

Vertical section through the interaction region
Bottom window
Top window
Molecule beam
Beam profiler
3" Corner (45 degre mirror)
690 J=0 from TA
aspheric lens
1090 from Nufern
aspheric lens
Cylindrical lens
for horizontal f=300
2" 50/50 BS
Cylindrical lens
for horizontal f=300

Stable Narrow Lasers for STIRAP



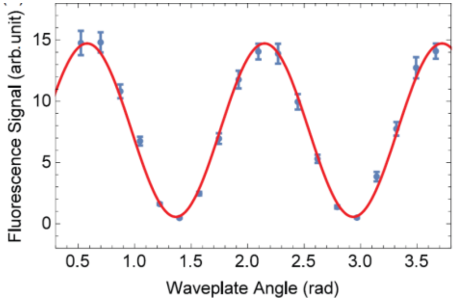


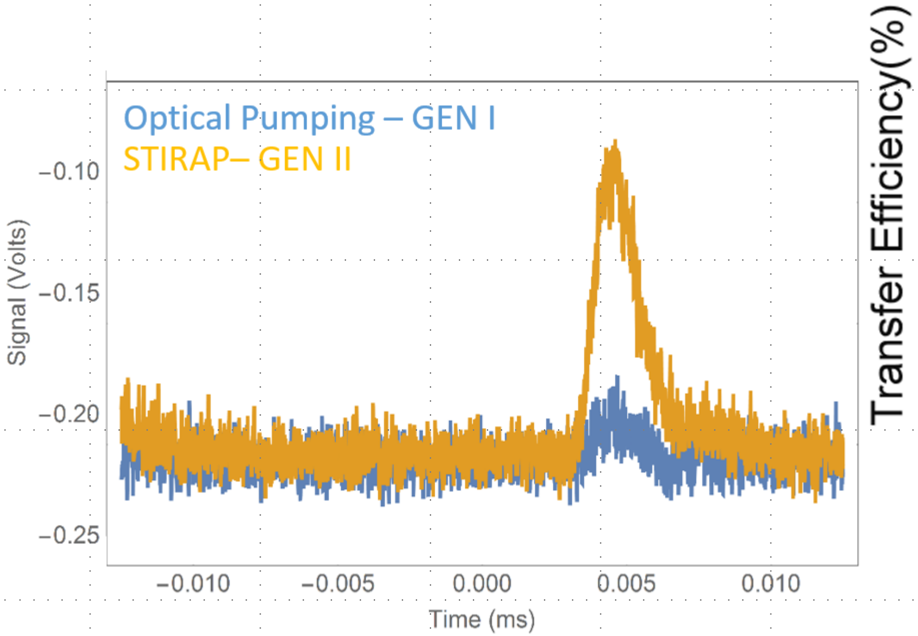




STIRAP Excitation – 12 Times Increase in Signal

coherent
superposition





Usable Molecular Flux Improvement Factors

What did not work so far: electrostatic focusing → made x-rays

What is working so far:

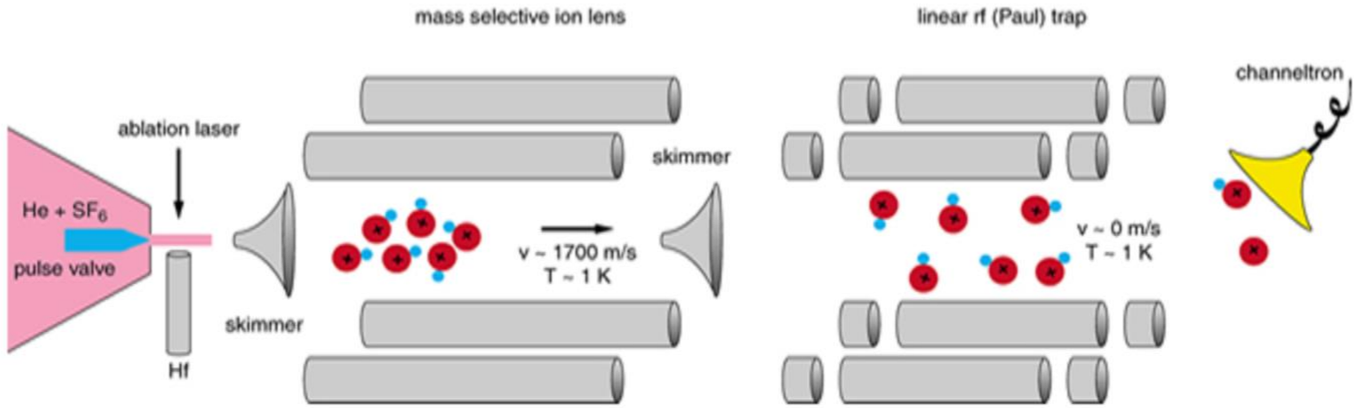
STIRAP	12
Light pipes rather than optical fibers	2.5
Higher quantum efficiency for 512 nm rather than 690 nm:	2
Improved solid angle	8
Total	~ 500
Statistical precision improvement:	~ 20

What may be close: thermochemical source rather than ablation

Other Electron EDM Measurement Aspirations to Probe Below Our 10^{-28} e cm

- **Imperial College:** YbF molecules (Hinds) 1×10^{-27} e cm

- **JILA:** Trapped HfH^+, HfH^+, PtH^+ molecular ions (Cornell, Ye)

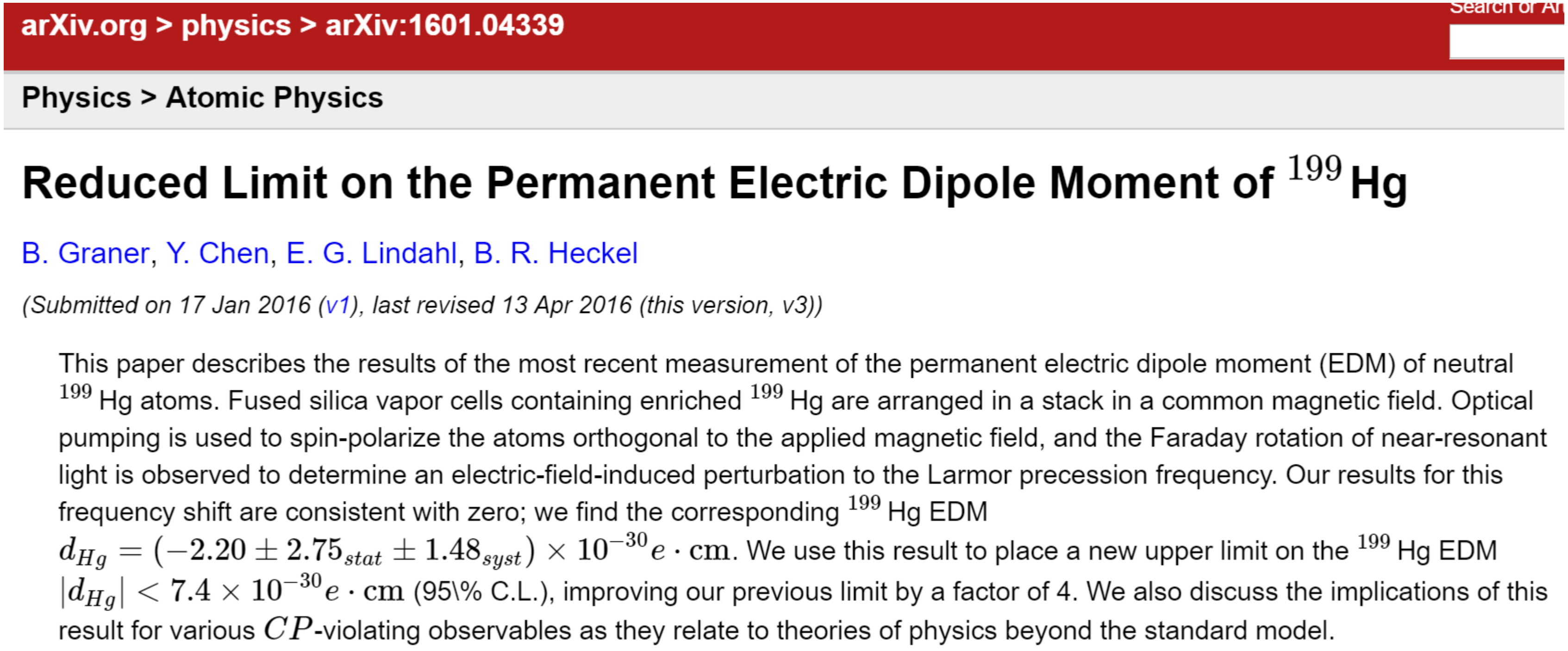


- **Penn. State:** extremely cold Cs and Rb atoms (Weiss)
- **U. Texas Austin:** cold trapped Cs (Heinzen)

Other Important EDM Measurements

Neutron EDM – earlier talk this session

Mercury EDM -- recent progress



arXiv.org > physics > arXiv:1601.04339

Physics > Atomic Physics

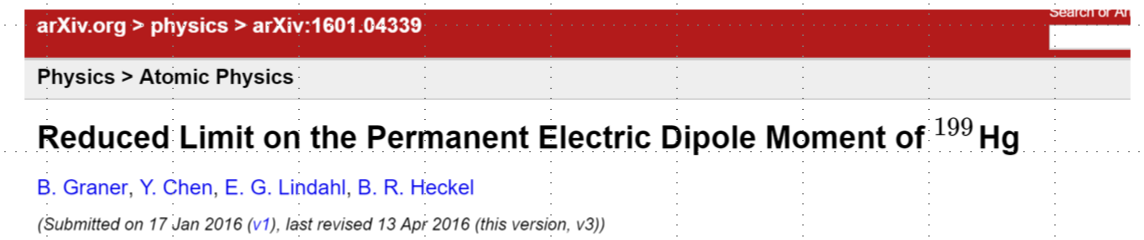
Reduced Limit on the Permanent Electric Dipole Moment of ^{199}Hg

B. Graner, Y. Chen, E. G. Lindahl, B. R. Heckel

(Submitted on 17 Jan 2016 (v1), last revised 13 Apr 2016 (this version, v3))

This paper describes the results of the most recent measurement of the permanent electric dipole moment (EDM) of neutral ^{199}Hg atoms. Fused silica vapor cells containing enriched ^{199}Hg are arranged in a stack in a common magnetic field. Optical pumping is used to spin-polarize the atoms orthogonal to the applied magnetic field, and the Faraday rotation of near-resonant light is observed to determine an electric-field-induced perturbation to the Larmor precession frequency. Our results for this frequency shift are consistent with zero; we find the corresponding ^{199}Hg EDM $d_{Hg} = (-2.20 \pm 2.75_{stat} \pm 1.48_{syst}) \times 10^{-30} e \cdot \mathrm{cm}$. We use this result to place a new upper limit on the ^{199}Hg EDM $|d_{Hg}| < 7.4 \times 10^{-30} e \cdot \mathrm{cm}$ (95\% C.L.), improving our previous limit by a factor of 4. We also discuss the implications of this result for various CP-violating observables as they relate to theories of physics beyond the standard model.

Sensitivity to Many CP Violating Observables illustrated in Recent Hg EDM Measurement



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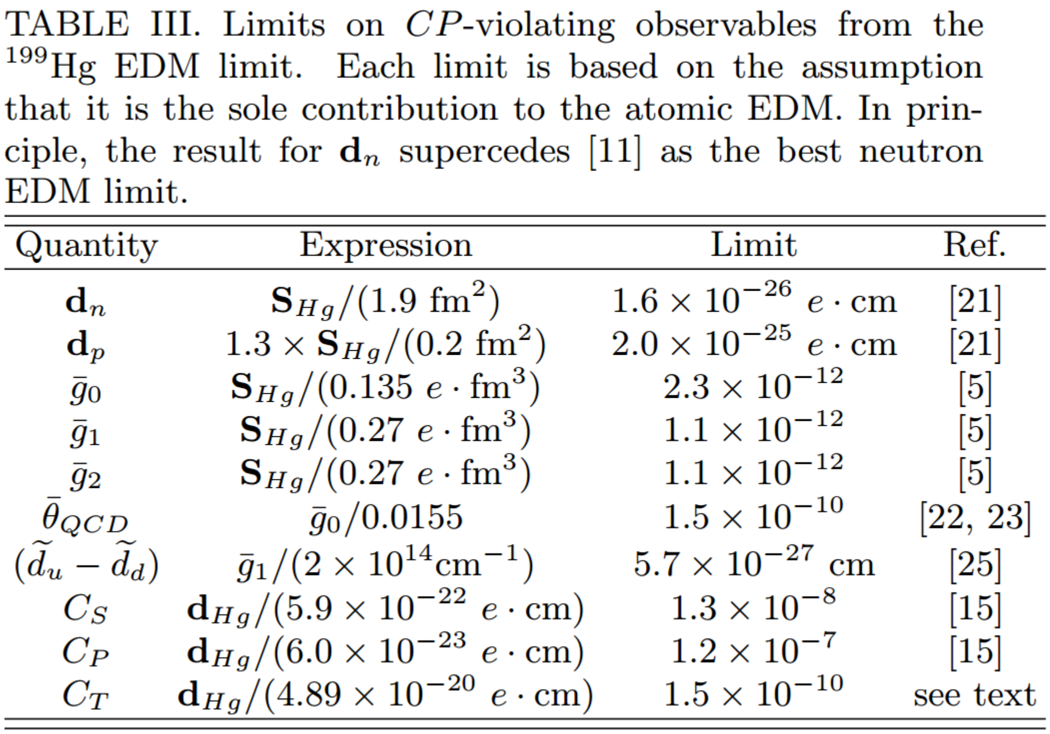
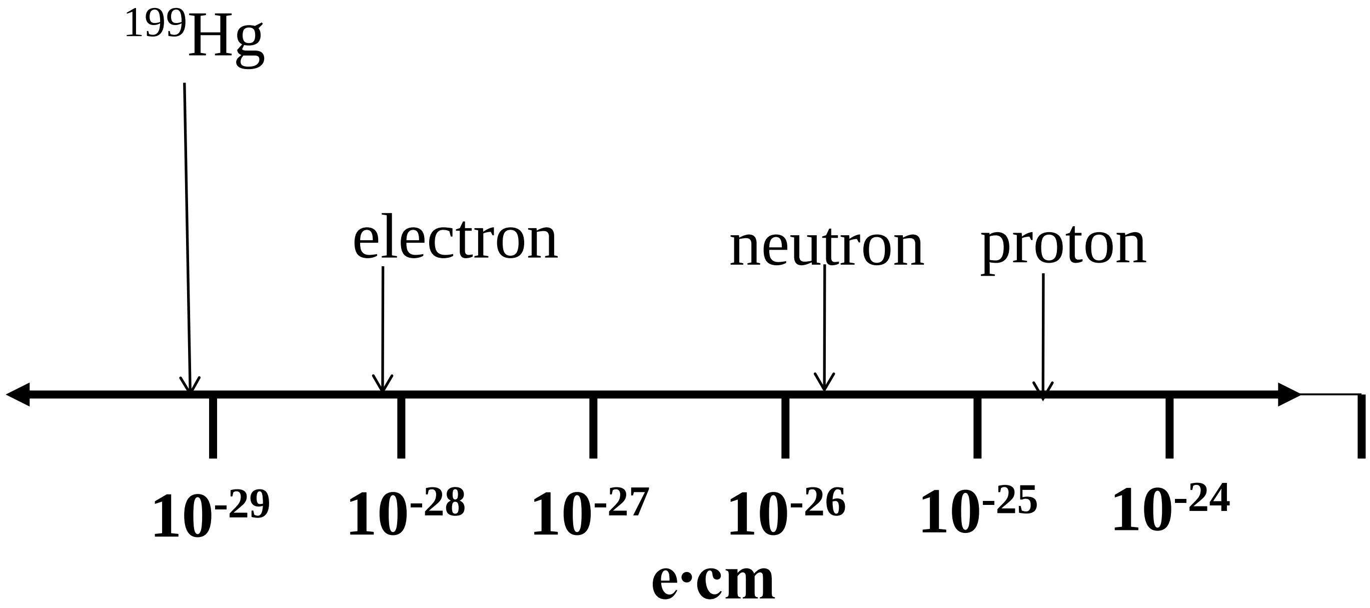


TABLE III. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{Hg}/(1.9\ \mathrm{fm}^2)$	$1.6 \times 10^{-26}\ e \cdot \mathrm{cm}$	[21]
$\mathbf{d}_p$	$1.3 \times \mathbf{S}_{Hg}/(0.2\ \mathrm{fm}^2)$	$2.0 \times 10^{-25}\ e \cdot \mathrm{cm}$	[21]
$\bar{g}_0$	$\mathbf{S}_{Hg}/(0.135\ e \cdot \mathrm{fm}^3)$	2.3×10^{-12}	[5]
$\bar{g}_1$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{g}_2$	$\mathbf{S}_{Hg}/(0.27\ e \cdot \mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{\theta}_{QCD}$	$\bar{g}_0/0.0155$	1.5×10^{-10}	[22, 23]
$(\tilde{d}_u - \tilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14}\mathrm{cm}^{-1})$	$5.7 \times 10^{-27}\ \mathrm{cm}$	[25]
C_S	$\mathbf{d}_{Hg}/(5.9 \times 10^{-22}\ e \cdot \mathrm{cm})$	1.3×10^{-8}	[15]
C_P	$\mathbf{d}_{Hg}/(6.0 \times 10^{-23}\ e \cdot \mathrm{cm})$	1.2×10^{-7}	[15]
C_T	$\mathbf{d}_{Hg}/(4.89 \times 10^{-20}\ e \cdot \mathrm{cm})$	1.5×10^{-10}	see text

Still No Particle EDM Has Yet Been Detected



also there are limits
on other parameter

Other EDM Experiments are Also Important

Other electron EDM measurements

- Check ACME result
- Different systematics
- If nonzero, atoms are more calculable
- Isotopes offer the chance to check and perhaps cancel systematics and and structure dependence

Neutron and Nuclear EDM

- Sensitive to other sources of T violation

Proton proposed (method more like ion trap method, next talk)

- Will it be possible to get needed sensitivity?

Summary

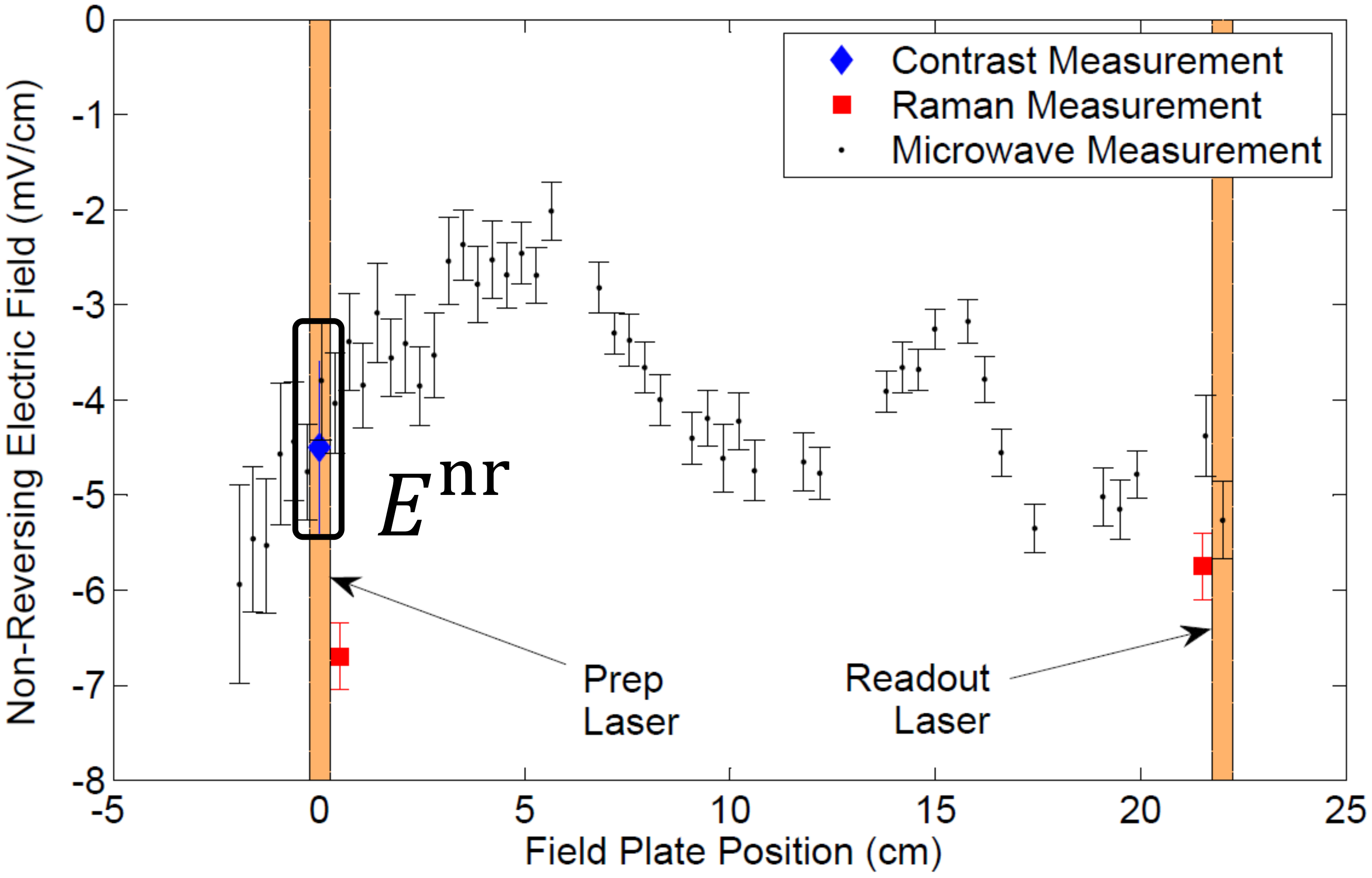
Electron Electric Dipole Moment

Despite a 12-Fold Improved Measurement
→ No electron edm yet

Probing for New Physics at TeV scales and higher
→ comparable or higher than the LHC

Substantial improvement in EDM precision seems possible
→ We are plunging on. > 10x improvement seems very likely

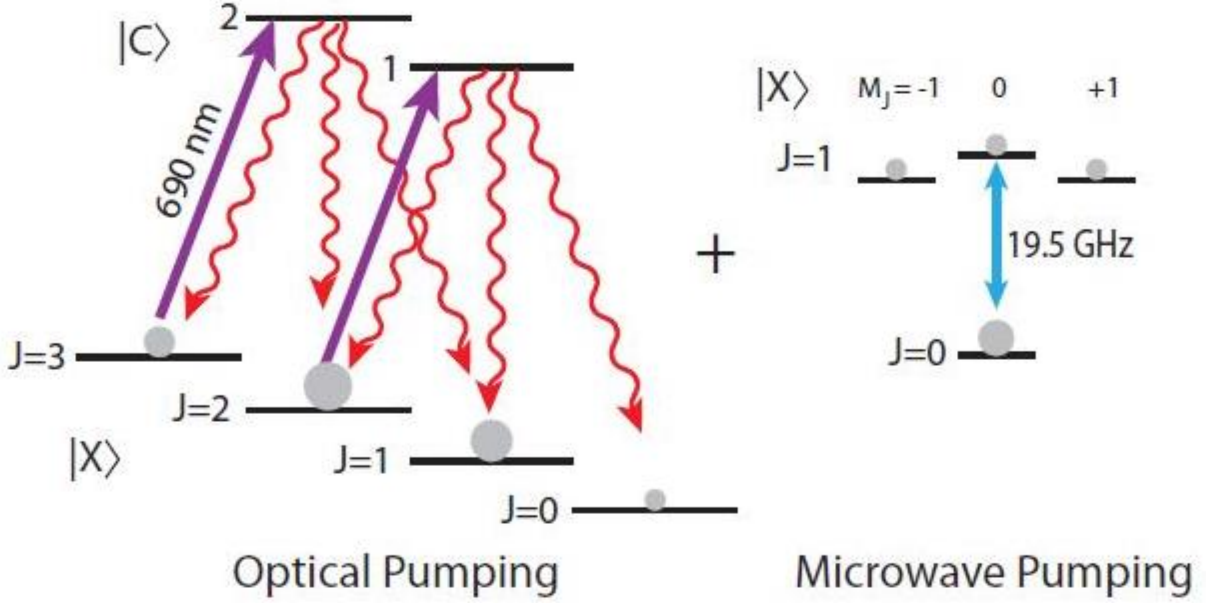
Patch Potential E^{nr}

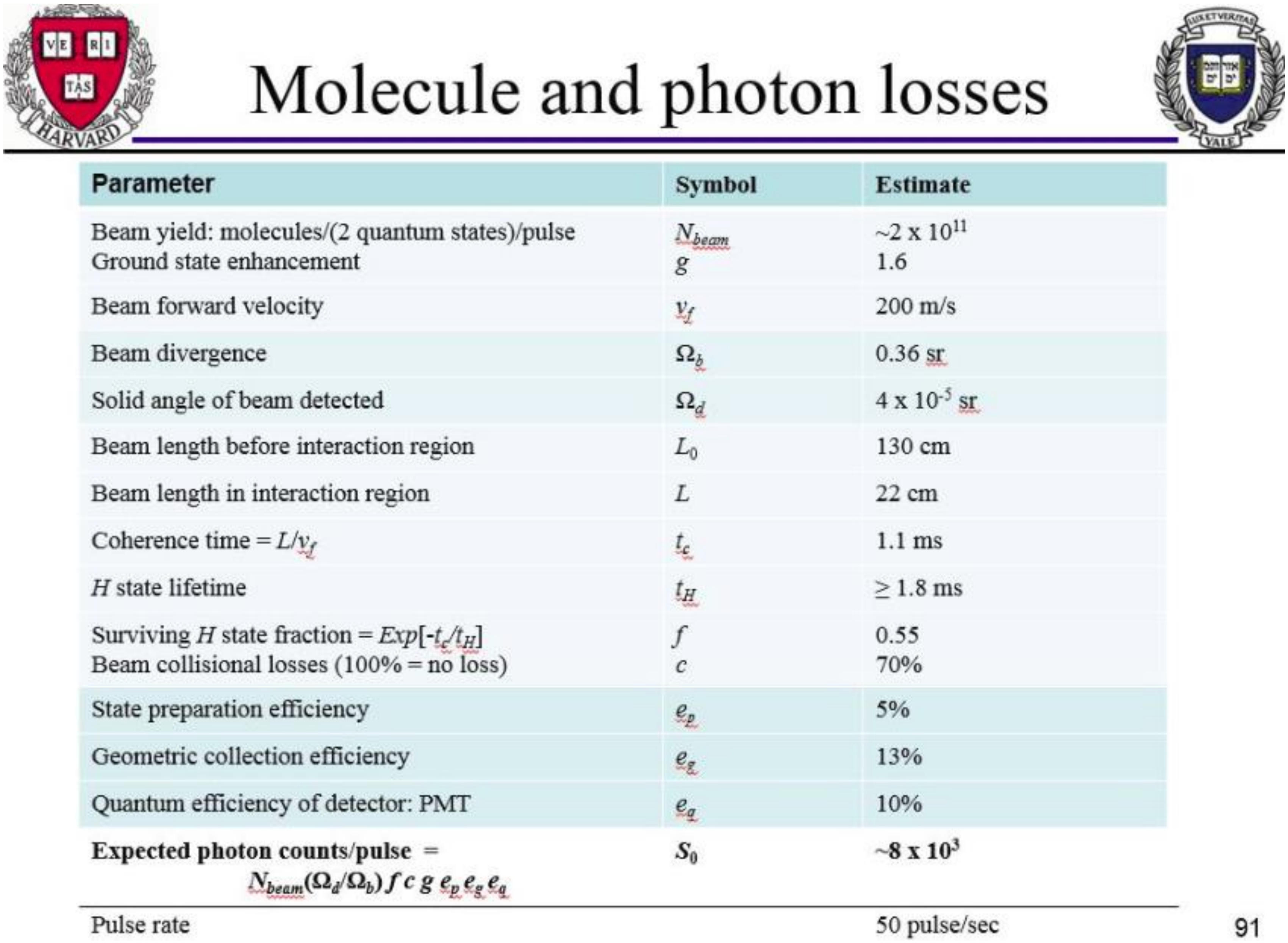


E^{nr}

$$\Delta d_e^{\mathrm{syst}} = S_{E^{\mathrm{nr}}} \cdot E^{\mathrm{nr}}$$

Prepare 17% of Molecules in the J=1 Ground State



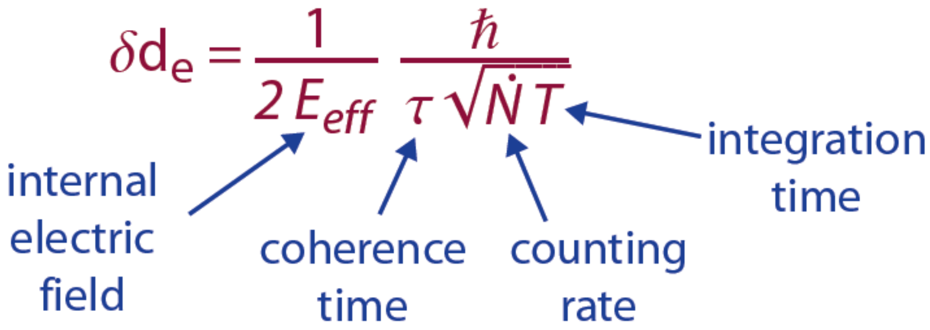


Molecule and photon losses

Parameter	Symbol	Estimate
Beam yield: molecules/(2 quantum states)/pulse	N_{beam}	~2 x 10^{11}
Ground state enhancement	g	1.6
Beam forward velocity	v_f	200 m/s
Beam divergence	Ω_b	0.36 sr
Solid angle of beam detected	Ω_d	4 x 10^{-5} sr
Beam length before interaction region	L_0	130 cm
Beam length in interaction region	L	22 cm
Coherence time = L/v_f	t_c	1.1 ms
H state lifetime	t_H	$\geq$ 1.8 ms
Surviving *H* state fraction = $Exp[-t_c/t_H]$	f	0.55
Beam collisional losses (100% = no loss)	c	70%
State preparation efficiency	e_p	5%
Geometric collection efficiency	e_g	13%
Quantum efficiency of detector: PMT	e_q	10%
Expected photon counts/pulse = $N_{beam}(\Omega_d/\Omega_b)\,f\,c\,g\,e_p\,e_g\,e_q$	S_0	**~8 x 10^3**
Pulse rate		50 pulse/sec

Statistical Comparison of ACME and Imperial

Statistical sensitivity:



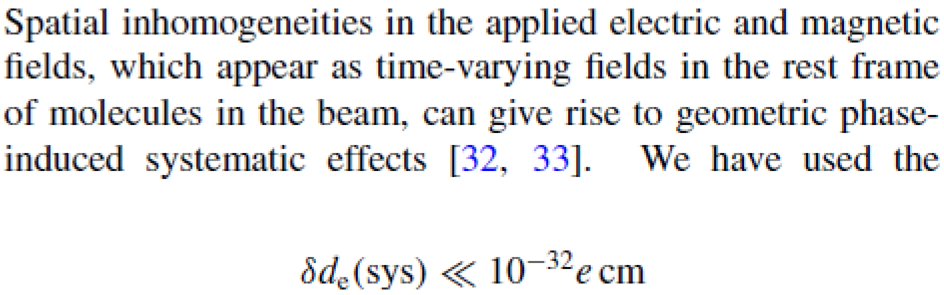
$$\delta d_e = \frac{1}{2E_{eff}} \frac{\hbar}{\tau\sqrt{\dot{N}T}}$$

7 x 1.7 x 2 = 24

	ACME ThO	**Imperial YbF**	
Effective E field	100 GV/cm	14 GV/cm	7
Coherence time	1.1 ms	0.65 ms	1.7
Photons/second*	1000 x 50 =50,000	500 x 25 =12,500	$4^{1/2}$
Precision in same time:	1	24	
Time for same precision	1	$(24)^2$ ~ 600	

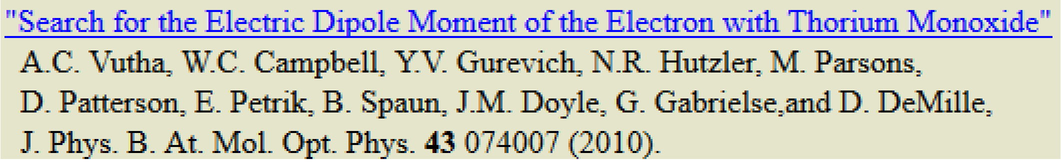
*Our molecule source is more intense, allowing us to use a metastable state rather than the ground state (as needed in ThO)

Berry’s Phase (Geometrical Phases)



Spatial inhomogeneities in the applied electric and magnetic fields, which appear as time-varying fields in the rest frame of molecules in the beam, can give rise to geometric phase-induced systematic effects [32, 33]. We have used the

$$\delta d_e(\mathrm{sys}) \ll 10^{-32} e\,\mathrm{cm}$$



"Search for the Electric Dipole Moment of the Electron with Thorium Monoxide"
A.C. Vutha, W.C. Campbell, Y.V. Gurevich, N.R. Hutzler, M. Parsons,
D. Patterson, E. Petrik, B. Spaun, J.M. Doyle, G. Gabrielse,and D. DeMille,
J. Phys. B. At. Mol. Opt. Phys. **43** 074007 (2010).

[34] Vutha A and DeMille D 2009 arXiv:0907.5116